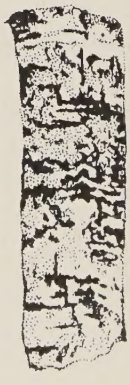
STRIAE

SOME PROPERTIES OF SULPHIDE-BEARING SEDIMENTS ON THE COAST OF NORTHERN SWEDEN

BENGT-ÅKE NYSTRAND



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STRIAE 13

SOME PROPERTIES OF SULPHIDE-BEARING SEDIMENTS ON THE COAST OF NORTHERN SWEDEN

By

Bengt-Åke Nystrand
fil. kand., skånelandens nation

Doctoral dissertation
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Some Properties of Sulphide-bearing Sediments on the Coast of Northern Sweden

BENGT-ÅKE NYSTRAND

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The present study deals with the physical and chemical properties of sulphide-rich sediments from northern Sweden, including their interaction and relation to geotechnical routine tests. The sampling was carried out in three different regions, all designated as areas of expansive building activity with problems related to the relevant sediment type. The sediments were investigated as to, *e.g.*, grain-size distribution, water ratio and bulk density, pH, ignition loss and carbon content, sulphur content, extractable iron and manganese, and exchangeable magnesium, sodium, potassium, and calcium.

The main part of the cores consisted of a pitch black sediment. On drying the sediment became lighter in colour and a characteristic banding appeared; the sediment showed an uneven shrinkage and a distinctive odour was emitted. Vertical fissures with oxidized coating in the fresh sediment hampered the geotechnical routine tests. The environment within the sediment is probably reducing and the black colour reflects the high content of metastable monosulphides. The ignition loss and carbon content show high values. The iron and manganese curves show different courses in the deeper layers of the sequence: the reason is not known. The exchangeable ion ratios, potassium/sodium, calcium/sodium, and magnesium/sodium reveal the expected salinity changes in the Litorina Sea. The SiO_2 in particular shows an interesting distribution which may be correlated with the transport capacity of the water during the sedimentation.

The sensitivity of the sediments from two localities is very high. This may be due to the unsatisfactory methods of testing. A fluid grey layer is extremely sensitive and thought to contain the slip surfaces of the land-slides. The investigation shows that routine methods do not yield satifactory results for characterizing the sediments, nor do they form a solid basis for practical application of the results.

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Fig. 1a. Distribution of land and sea about 6500 B.C., time of the Ancylus Lake's greatest extent (from Fromm 1953 in National Atlas of Sweden).

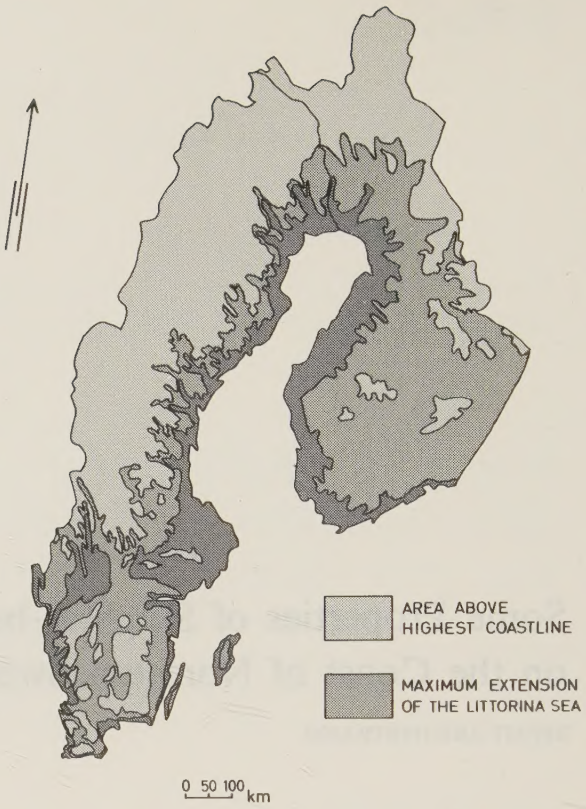

*Fig. 1b.*Distribution of land and sea about 4500 B.C., time of the Littorina Sea's first maximum. The map has been modified from Fromm (op. cit.) with respect to the highest coastline.

Introduction

Sulphur-rich, silty sediments—sulphide soils (Swedish "svartmocka")—are found in the coastal areas of northern Sweden and Finland (Figs. 1a and 1b). These soils are of particular interest as representing a major obstacle to building and construction. The reason is that standard methods of discovering the geotechnical properties of soils, *e.g.* shear strength and deformation, often give misleading results.

Landslides are not uncommon in these areas (Wenner 1951, Jerbo & Sandegren 1962, Jerbo 1969). Many may be described as sheet slides (Záruba & Mencl 1969). When trenches are excavated for conduits it often happens that the sides collapse. Thus this type of work must be executed with care as planning and realisation may well prove extremely costly. Despite precautionary measures accidents are frequent.

Furthermore, when laying foundations on sulphide soils it is difficult to predict the consequences in the form of distortion and breaking-tenacity of the soil. For reasons of safety builders must have recourse to more expensive constructions which, on the basis of the geotechnical investigations, would not normally be necessary. In spite of precautions, however, major unexpected deformations and failures frequently occur. The causes of the divergence from the behaviour of "normal" post-glacial sediments can be, *e.g.*, mineralogical composition, stratigraphy, content of organic matter, micro-biological activity, and chemical properties of the sediment and/or the interstitial water. Other reasons relate to the hydrogeological properties of the bed sequence, such as pore pressure and pattern of ground-water flow. All these factors will to a greater or lesser extent influence the geotechnical properites of the sulphide-rich sediments. The present study deals with their physical and chemical properties, their interaction and their relation to geotechnical routine tests.

Literature review

This section presents the sulphur soils in the Bothnian areas (Fig. 2) mainly in accordance with the literature. The account deals with the characteristics, formation, appearance, extent, general stratigraphy and age of the sediment.

Sulphide soils in the Bothnian area.

Sulphur-rich fine-grained sediments have been described from different parts of Sweden. They are particularly frequent along the northern seabord from Gävle to the Finnish border (Lindström 1888, Blomberg 1895, Högbom 1922, Granlund 1943, Jerbo 1965, Modig 1967, Ericsson 1970, 1973, Nystrand 1970). These types of sediment have also been observed in the Gulf of Bothnia and the Bothnian

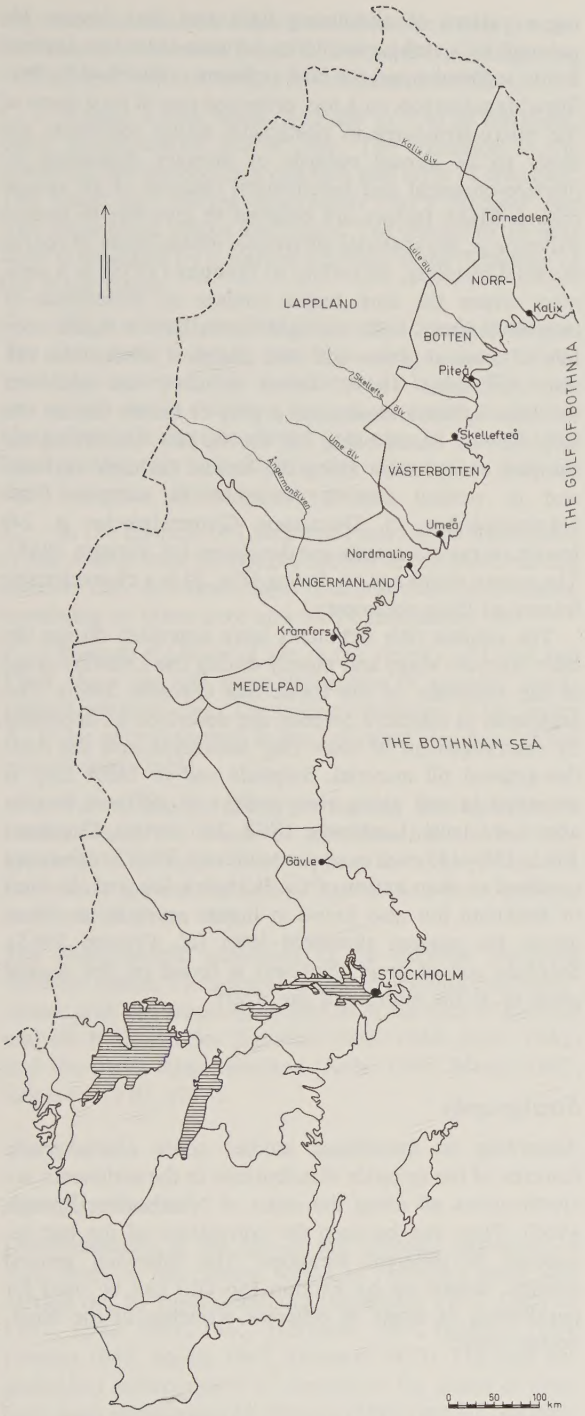

Fig. 2. Map of Sweden showing sites and provinces mentioned in the text (from National Atlas of Sweden, 1958).

Sea (Mölder 1946, Debyser 1957, Purokoski 1958, Peltola 1960, Ignatius 1964, Jerbo 1965).

Differences exist as to thickness, grain-size distribution and ignition loss in sulphide soils from different regions and also in the geochemistry, see below. The sediment generally consists of pitch-black medium clay or gyttja clay. Fresh samples taken under the dry crust usually show only a faint pattern of lighter and darker bands. After a few minutes' contact with the air, however, distinct bands appear.

The reducing environment is a condition for the sulphide formation. The reducing conditions may be restricted to the actual sediment as in the case of microbacteriological decomposition by means of specific microbes, *e.g. Desulfovibrio* sp. which is crucial for the metal sulphide formation (cf. Wedepohl 1970). The reducing environment may also include the water covering the sediment surface as in restricted deep water basins where the oxygen is wholly or almost wholly consumed. This redox-potential-discontinuity (RPD) zone — Eh=0 — is of great significance in the discussion of the conditions for chemical activity in a sediment. The RPD zone has been studied by many authors and reported from many parts of the world. The classic work is that of Androussow (1897) on the Black Sea.

The reducing conditions occur in normal shelf sediments at a depth of a few cm under a layer of oxidized sediment (see, *inter alios*, Manheim 1961, Ignatius 1964, Borchert 1965, Cato *et al.* 1978). In areas with a large supply of organic matter, the redox-potential-discontinuity zone may ascend to the sediment surface (cf. Cato 1977) and in stagnant basins even up into the water above it (cf. Olausson 1972, 1975). Fonselius (1969) summarized the oxygen deficit in the Baltic as due to:

> the increased salinity which has increased the stability of the halocline and diminished the supply of oxygen to the deep water through the halocline.
>
> the higher proportion of phosphorus in the Baltic which has increased the primary production and indirectly, thereby, the oxygen consumption in the deep water.

The salinity increase is the primary and the phosphorus increase the secondary cause of the oxygen deficit. But other factors may cause oxygen deficit in the water environment, such as, *e.g.*, the often created thermocline in the summer and winter seasons, the ice sheet and to some extent the organic production which affects the density of the water (Fonselius 1969). The supply of oxygen to stagnant bottom-water is mainly due to increased vertical water circulation in spring and autumn, and sudden inflow of salt water or cold fresh water. This mainly originates from the annual melt of ice and snow. Another factor which may play a part is transgressions and regressions which could exert a long term effect on the water circulation.

The amount of oxygen available in a sediment naturally influences the aerobic breakdown of the organic matter and the subsequent decrease of the pH. In the absence of available oxygen the further oxidation of the organic matter as mentioned above takes place by means of anaerobic bacteria using sulphate ions. In consequence of this process the pH in the sediment tends to increase as the release of nitrogen leads mainly to the formation of ammonia and the H_2S or HS^- formed results in a weak acid, balanced by a strong base (cf. Biggs 1967, Olausson 1972). The carbon dioxide is, however, the main factor controlling the pH of the sediment.

The mechanism of the black colouring of sediments has been investigated by many authors (see, *inter alios*, Mor-

timer 1941, 1942, Hayes 1964, Papunen 1968 and Fonselius 1969). In their opinion hydrous oxides of iron are reduced to the ferrous state in the deeper reducing layer of sediment. The dissolved iron may then migrate upwards through the interstitial waters by diffusion and/or sediment compaction, prior to subsequent precipitation in the topmost oxidated layer of the sediment. However, the sediment surface can become reducing long before the water above it has lost its oxygen (Fonselius 1969) and many sediment substances may then to some extent be released to the supervening water mass.

If iron-reducing bacteria and/or H_2S are present both the migration and the release of iron from the sediment are diminished or interrupted as the ferrous ions immediately react with H_2S to form iron sulphides (Wedepohl 1970).

The production of sulphide decreases both Eh and pS^{2-} of the sediment and pyrite becomes the most stable form of iron sulphide. According to Berner (1964) the reaction of H_2S with ferric minerals and dissolved ferrous ion results first and foremost in the formation of one or more poorly-crystallized, acid-soluble black iron monosulphides, machinawite (FeS) and/or greigite (Fe_3S_4) which transmit their black colour to the sediment. In relation to the stable iron sulphide pyrite, they are thermodynamically labile in sediments. The disappearance of the black colour with increasing depth is a result of the gradual conversion to the more stable iron sulphide pyrite (cf. Berner 1967, 1971).

The iron reacting with sulphide ions may, according to Papunen (1968), also be bound to organic compounds, very likely to humic acids occurring as colloids in water and sediments. But the iron is weakly bound to the humic colloids, as it can still react with, *e.g.*, sulphide ions. The bond may have weakened by reasons of the increasing acidity and coacervation of the colloid. If the sulphur does not suffice to form stable disulphides, black pigmentous monosulphide forms and persists, in combination with colloids. According to Berner (1971) the amounts of iron sulphide which may be formed in sediments are limited chiefly by the following factors:

the concentration and reactivity of iron compounds,

the availability of dissolved sulphates,

the concentration of degradable organic matter.

The third factor is adjudged the most important as the concentration of degradable organic matter is directly related to the rate of sulphate reduction in a sediment. The rate of reduction therefore depends on the amount of organic matter available. This reduction may lead to high concentrations of hydrogen sulphide in the interstitial waters, thus, directly influencing the formation of iron sulphides when sufficient iron is present (cf. Berner 1971, Cato 1977).

The banding of the sediment is of late origin, a result of chemical changes (diagenesis) within the sediment. According to Gripenberg (1934:97) all original stratification has disappeared and "the 'layers' have coalesced into 'reducing areas' of varying dimensions". Perfiliew (1933) describes well-developed micro-structures, "microzones", recognized in postglacial lake sediments. Ignatius (1958) investigated material from the Baltic sediment basins and found that the banding was sometimes quite regular, showing a pattern of alternating light and dark layers. He pointed out a striking similarity between these thin-layered Baltic sediments and the lake sediments described by Perfiliew. Ignatius (*op. cit.*), too, proposed that at least some of the micro-structures in postglacial Baltic sediments are likely to be annual records of primary deposition or physico-chemical and biochemical features of an annual nature. Many factors are believed to give rise to annual varves, *e.g.*, the seasonal differences in the supply of coarse material resulting, according to Ignatius (1958) in a sediment where the dark bands contain an abundance of organic material while the light bands have a higher content of mineral grains and also chemical precipitates (cf. also Arrhenius 1947). When oxidized the sediment becomes lighter and assumes a grey or brown colour, the sulphide-rich bands being still the darkest. On drying the samples easily crack along the bands. On their surfaces and in vertical fissures (common in samples from Gammelgården; cf. Discussion Gammelgården p. 24) brown layers of limonite are developed (cf. Fromm 1965). The severe shrinkage on drying (Fig. 3) is a characteristic feature of these sediments.

The sulphur-rich sediments were deposited during the later Ancylus stage and mainly during the Littorina stage in the evolution of the Baltic Sea (Fromm 1965). The sediments in northern Sweden are described as deposited by rearrangement of older clay sediments and the most fine-grained till material. Sulphide soil or black clay is observed in and along river valleys at different heights above sea level (Lindström 1888, 250 metres, Granlund 1943, 130—135 metres above sea level). They are thus not confined to deep basins of the Bothnian Sea and the Gulf of Bothnian but also found in higher areas up to 50 m above the present threshold level (cf. Fromm 1965). Sulphide soil of great thickness is found on the coastal plain or at the mouths of the rivers.

Stratigraphy

According to microfossil studies some characteristic features of the sulphide distributions in the sediments are synchronous all along the coast of Norrbotten (Fromm 1965). They can be used for correlation of the bed sequences of different localities. The following general scheme, drawn up by Fromm (op cit.) can be used for parallelling of strata in different stretches of the Norrbotten coast.

A. — The top layer consists of dark grey-blue to blue-black homogeneous coarse clay from about 1 m to over 5 m thick. In the dry crust the clay becomes grey and contains rust-coloured spots.

B. — Fine-bedded or banded coarse clay. The clay is characterized by black distinct bands separated by slightly brighter, dark-grey clay. Moreover the groundmass of the clay displays a distinct stratification. Therefore, when the clay dries, it easily splits along the bands. The distance between the separate sulphur-bands is about 0.5—1 mm. The banding is probably due to seasonal fluctuation in the organic production of the sea. The thickness of the separate bands seems somewhat greater in the cases where

the total thickness of the fine-banded coarse clay is greater. The boundary between B and C is often sharp (cf. Ignatius 1958, Jerbo 1965, Modig 1967, Ericsson 1973).

C. — Rather a thin layer, 1–2 dm to 1 m in thickness, black homogeneous coarse clay. The transition to the overlying fine-banded clay can be a thin layer of grey clay. The black clay merges downwards into a medium clay with close black stripes and bands. The change to the next layer is indicated by a marked decrease in the frequency of the black bands.

D. — Black-striated medium clay, 1 to 2.5 m in thickness. The clay itself is bright grey-blue with a characteristic weak nuance in red with black bands, or layers. These are one or two mm in thickness but not as regular as the thin black bands in the fine-varved light clay of layer B. The black bands are a little closer in the upper part of layer D; their frequency diminishes downwards.

E. — In the districts of Luleå and Piteå but no other parts of the coastal area the bottom section of the black-banded medium clay contains a layer 1 or more dm in thickness, consisting of often pure and well consolidated silt.

F. — Beneath the layer of silt, in the vicinity of Luleå and Piteå, there are still some decimetres of sparsely black-banded medium clay. The colour variations in the layers A–F are only preserved in the saturated clay beneath the ground-water table.

G. — Varved clay. In the dry-crust clay the sulphides are oxidized and the black or grey-blue colour has disappeared. The layers A–C appear as a grey, fissured, rather rust-spotted, light clay, layer D as a homogeneous redbrown medium clay.

The characteristic variations in the sulphide colouring decrease inland. The general sequence of strata can be correlated with sequences described from the Gulf of Bothnia and the Bothnian Sea (Ignatius 1958, 1964, Jerbo 1965) and also from Ångermanland (Jerbo 1965, Modig 1967, Ericsson 1970, 1973).

Age of sediments

Determinations of the age of the different sequences of clay strata in the coastal region of Norrland have been carried out by several authors (Granlund 1943, Debyser 1957, Jerbo 1961, 1965, Hörnsten 1964, Ignatius 1964, Fromm 1965, Modig 1967, Ericsson 1973). The ages and geological environments of deposition for strata of clays have been investigated by Fromm (1965) at four representative sites in Norrbotten. He examined the profiles by palynological and microfossil studies (Fromm 1949, 1965).

For the strata A–F described above the following age relations and depositional environments are valid according to Fromm (1965).

A. — This sediment was deposited in brackish water during the later Littorina stage up to the present day. The sea level was then about 35 m higher than now.

B. — Littorina B, 5000–3000 B.C., is dominated by a brackish flora. According to pollen analysis this part probably corresponds to the high maximum of birch during the warm period.

C. — This part of the sequence marks the first influx of brackish water into the Gulf of Bothnia at the beginning of the Littorina stage. This phase is called Littorina A and dates from the centuries just after 5000 B.C. The mixed oak forest appears, dominated by the elm. The sea level of the Baltic was probably about 100 m higher than today.

D. — This part of the sequence contains the pine maximum of the Boreal period which occurred in the Ancylus stage. The fresh water diatoms are characteristic of the Ancylus Lake.

E. — At some sites a varve, one or more dm thick is found, consisting of silt, possibly a drainage varve.

F. — The Yoldia stage in a very fresh water environment, which appears more or less marked according to geographical location.

Investigation sites

The investigation sites were selected after discussion in the project group (see below p. 48). Areas which are or were expected to be subjected to expansive building operations were deemed appropriate. Furthermore the sites were chosen with respect to their geographical distribution for the purpose of comparing sediments from different parts of the coastal area of northern Sweden.

Gammelgården

Only in the lower Tornedalen valley can the traditional division of northern Sweden into a coastal plain and a hinterland intersected with valleys be used. In other parts of Norrbotten the difference between these two units is less marked.

The broken ground gradually decreases from interior out to the coast. The broken terrain has spurs which end at the present coastline, where isolated hills reach a height of about 100 m above the surrounding plain (S. De Geer 1926, Ahlmann, Laurell & Mannerfelt 1942, Enequist 1946, G. Lundqvist *et al.* 1963, Fromm 1965). The littoral area continues into the hinterland along the great valleys. Particularly in the south-western and north-eastern parts of the county it is complex being composed of a number of peneplain facets in the form of a staircase (Fromm 1965, Rudberg 1954, 1956).

The investigation site was chosen with reference to previous studies (internal reports at the Swedish Geotechnical Insitute, National Road Administration). Previous investigations describe the soil as a sulphide soil. The resistance according to the weight-penetration test, and the shear strength are poor. Furthermore the National Road Administration encountered problems in the building and maintenance of roads in this region. The results of the investigations from this site concentrate on these problems.

The site is located about 6 km north-west of the town of Kalix along the main through road number 390 from Gammelgården to Börjelsbyn, a few km above the mouth of the River Kalixälven in the Gulf of Bothnia. The ground within the investigated area is about 3 metres above sea level. The river flows through moraine areas and discharges into a funnel-shaped widening in the Gulf of Bothnia. No delta is formed. The reason is probably that

further upstream the river widens at several points into "lakes" which serve as traps for coarser sediments (sand, fine sand). Where the river flows gently the deposition of clay has continued, even where the water is shallow because of uplift of the land. The coarse clay deposits have a higher content of organic matter near the surface. It can be classified as a gyttja-clay. Such deposits are found near Gammelgården. Fine-grained sediments of considerable thickness are deposited in the lower reaches.

Rödäng

Rödäng is located in the province of Västerbotten, which is briefly described by reason of its topography.

North of the town of Skellefteå there is a flat littoral plain decreasing inland. Further south the terrain is broken. The soil cover is very thick north-east of Umeå. The bedrock is, however, exposed at many places. South-east of Umeå there is a littoral plain which often shows thick moraine formations with an even transition to the broken ground. Nordmaling is surrounded by a marked littoral plain with a sharp border to the so-called square table-land (Swedish *rutplatålandskapet*; Rudberg 1954, 1956). Southernmost Västerbotten is dominated by the very broken ground which is characteristic of Ångermanland, further to the south. The flat littoral plain continues inland along the river valleys (Högbom 1906, Granlund 1943).

The investigation site at Rödäng was chosen in consultation with the Umeå municipal building committee. The committee arranged for weight penetration tests, observations of the ground-water table and piezometric surface together with test loadings within the area.

The site is located within the town of Umeå, in its north-western part, just north of the main through road number 92 between Umeå and Vännäs. It is situated below the highest coastline on the coastal plain, about 9 m above sea level, in the valley of the Ume älven river where the valley is crossed by an esker which runs along the upper reaches of the Vindelälven river down to the coast.

Dynäs

In the province of Ångermanland the terrain is extremely broken. There are mountains of considerable height even at the present shore-line. In gulfs and river valleys the sediments may be up to 15 m thick.

The Dynäs investigation site is situated on an estuary, the Bay Bollstafjärden at the mouth of the Ångermanälven river about 200 m south-east of Dynäs railway station, and 4 km NNE. of Kramfors (Figs. 2 and 4). The site was chosen in consultation with the Kramfors municipal building committee and lies in the valley of the Ångermanälven river about 40 km from its mouth. It is situated about 4 km south of the recent delta (cf. Arnborg 1959) of this river. The highest coastline levelled at Mt. Skuleberget lies at an altitude of 285.5 m (Hörnsten 1964), the investigation site at about 6.6 m.

Methods

Sampling and in situ determinations

In order to obtain samples of undisturbed soil for physical and chemical analyses a Standard Piston Sampler, St I (Flodin 1961, Kallstenius & Hallén 1963) was used. The punching level, *i.e.* the limit between the middle and lower sample tube, was precisely determined via a wooden construction with a fixed level. Complete sets of samples were taken from three holes in order to provide a continuous series of samples from the surface down to firm bottom. These were about two m apart, the minimum distance recommended to avoid interference between the holes (Kallstenius & Hallén 1963). On sampling, the punching level is displaced 34 cm downwards from one hole to the next. A continuous sequence is thereby attained, with overlaps between the upper and middle and the lower and middle tubes (Fig. 5).

A ground-plan of the Dynäs site is shown in Fig. 6. The general arrangement is repeated at the Gammelgården and Rödäng sites. The sampling holes are thus grouped three by three. This makes it possible to arrange the samples in a continuous core sequence.

The samples from holes 1–9 are described for the Dynäs site. Furthermore, water-table observations were performed in hole 16. The routine technical tests are reported from the sampling groups 1–3, 4–6, and 7–9 while the chemical analyses were performed on samples from holes 4, 5 and 6. The sampling groups 1–3, 4–6, and 7–9 will be adduced as A, B and C respectively. The field-vane tests were made at points 17 and 18.

Water ratio, bulk density, shear strength (fall-cone tests, field-vane tests and undrained compression tests) were determined in the three areas A, B, and C, for the purpose of establishing whether the sampling density influences the curves. In the most sparsely tested core the test interval varies between 34 and 68 cm, in the next it is 34 cm and finally, in the third, 17 cm. The most common method used in soil investigations for geotechnical purposes, consists of sampling at each m of depth.

According to Broms (1976) the soil volume investigated usually corresponds to only 1/10 000 000 of the soil volume later influenced by overburden. As the estimates are made on a single sample from each depth the risk of mistakes seems striking as there are many sources of error in the sampling (*e.g.* changed conditions within the sample, changed temperature of the sample), the transport (temperature and vibrations) and the testing of the sample. As for chemical analyses of soil samples, double tests should be routine.

Analyses which had to be carried out immediately after sampling, on fresh soil samples, *e.g.* determination of water ratio, pH, Eh and description and photography of the cores were performed in a mobile laboratory (Fellenius 1955) near the investigation site, except in the case of Rödäng. Samples for other determinations were sent by express delivery to a soil laboratory. Storage of samples was avoided as far as possible in order to prevent alteration of the natural attributes, *i.e.* pH, Eh and geotechnical properties. Apart from the mode of sampling, temperature changes, changes in prevailing stress-strain relations, alteration and vibrations influence these properties.

When sampling with a Standard Piston Sampler the most intact samples are obtained from the middle tube and the upper part of the lower tube. These samples were used for physical and chemical analyses. Outer, oxidized soil was removed. Most of the analyses were performed in the soil laboratory at the Department of Quaternary Geology, University of Uppsala, the chemical laboratory at the Upp-

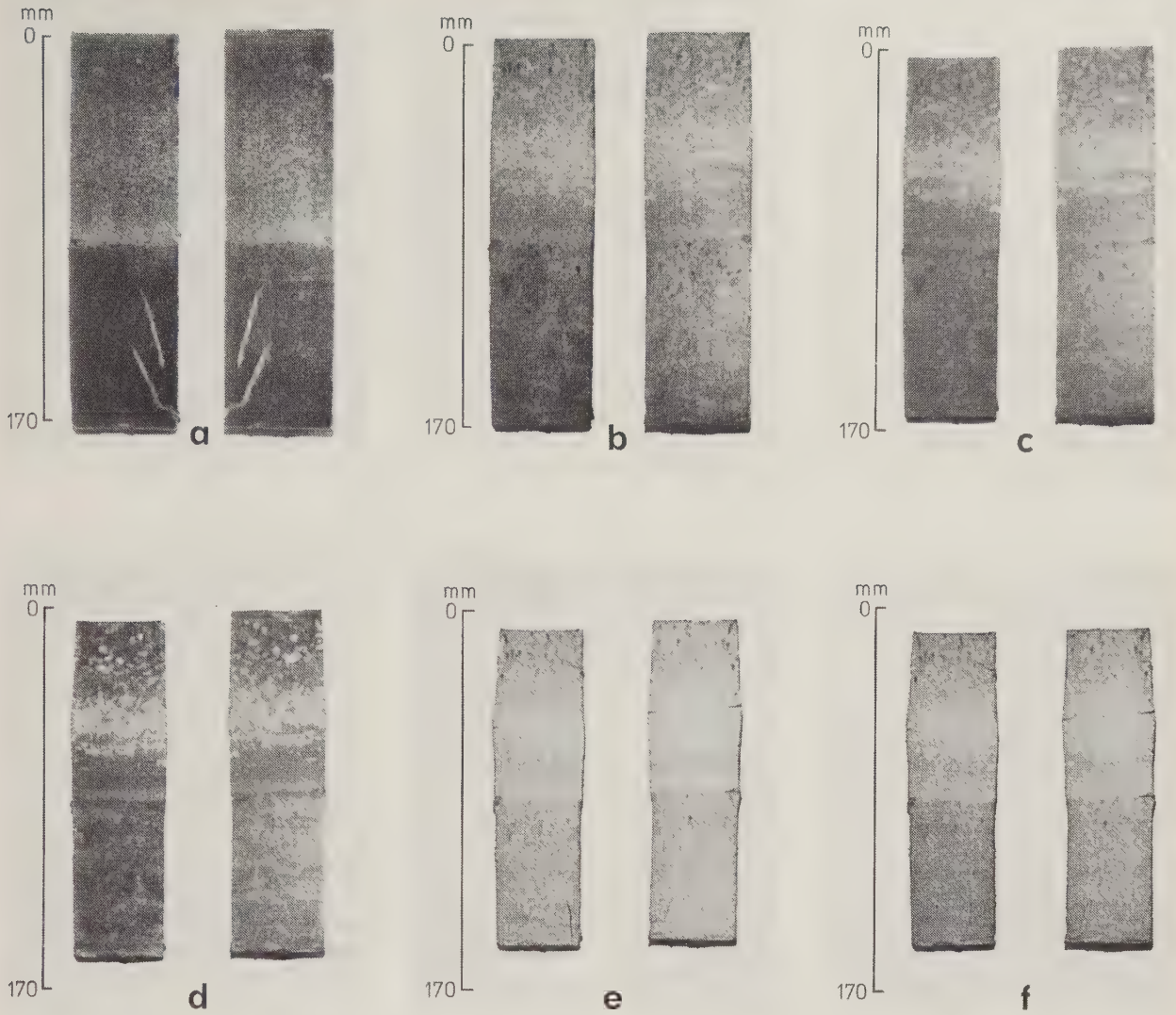

Fig. 3. Photos, a to f, illustrating the shrinkage when exposed to air at room-temperature of a piece of core cut in half. The upper part of the soil sample corresponds to a depth of 1.40 m below surface and the lower to 1.57 m down. There is a marked limit 9.5 cm below the upper border of the samples. After 24 hours (photo b) the sample is oxidized and "structures" can be seen. No shrinkage in length is discernible. After 55 hours the sample is about 0.6 m shorter and the structures are distinguishable. After 96 hours the sample has shrunk about 2 cm in length and there is an irregular reduction of its width. After 191 hours the shrinkage in length is about 3 cm and the decrease in width still clearly visible. Further more horizontal fissures are present one at the sharp limit mentioned above one at about the middle of the upper part of the samples. After 214 hours no changes are observed.

sala Institute of Palaeontology, and in the Geotechnical laboratory at Swedish State Railways.

A continuous core was taken at Rödäng for photography and pollen analysis by means of a Foil Core Sampler (Kjellman *et al.* 1950). The shear strength of the soils *in situ* was determined with a field-vane apparatus, type Jonell-Nilcon (Broms 1972).

At Dynäs the piezometric surface was observed during a period of 90 days, in an open tube ϕ 5 cm pressed down to a depth of about 11 m in the grey varved clay.

Laboratory work

Bulk density. — The bulk density, γ, defined as the total mass divided by the total volume, was determined for all samples. The determination was performed by weighing the sample tube while full of soil (Pusch 1973).

Water ratio. — The water ratio is given in g per 100 g dry weight (%). The determination was made on undisturbed samples by measuring the loss of weight on drying to constant weight at 105°C, usually during 24 h (Pusch 1973). When interpreting water-ratio figures it is essential to bear in mind that the water ratio depends on several factors, *e.g.*, mineral composition, grain-size distribution, compaction, and organic matter content of the sediment (Terzaghi 1946, Cato 1977).

Grain-size distribution. — The grain-size distribution was determined by means of the hydrometer (Bouyoucos 1927,

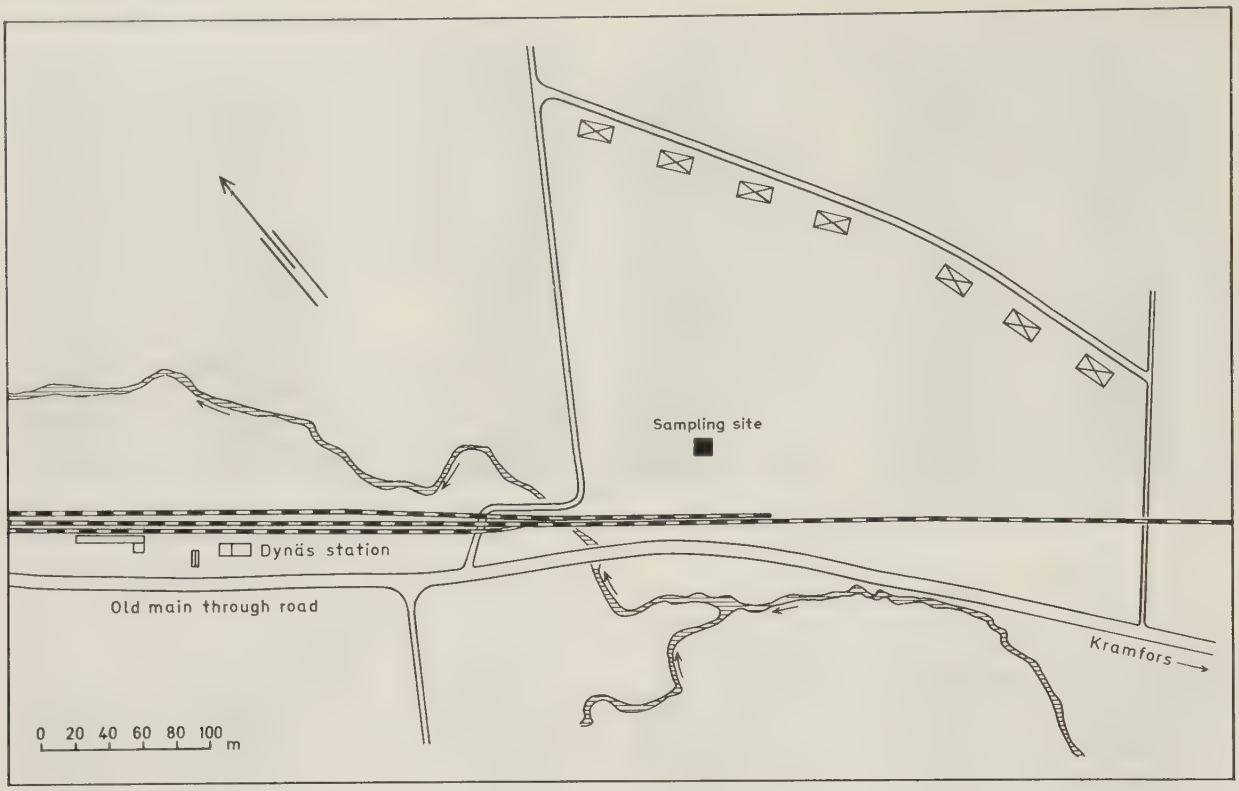

Fig. 4. Map showing the sampling site at Dynäs.

Gandahl 1952) and, to some extent, pipette methods (Krumbein & Pettijohn 1938).

The analyses were performed with minimum pretreatment of the samples in order not to impair the natural soil aggregates, as their composition and size-distribution greatly influence the geotechnical properties of the soil. The pretreatment was confined to gentle crushing of the larger aggregates in a mortar and dispersion with a water solution of 0.005 M sodium pyrophosphate in an end-over-end shaker.

Despite the gentle pretreatment a certain destruction of the aggregates presumably takes place, resulting in too high percentages for the finer fractions. On the other hand a high proportion of aggregates—very probably the majority—remain more or less intact. This statement is confirmed by comparison with grain-size-distribution curves of more widely dispersed samples of similar soils from neighbouring areas (Modig 1967, Ericsson 1970). Similar results were noted on mechanical analysis of 11 samples from Dynäs, boiled with hydrogen peroxide (Stål 1972) in order to remove the humus (see below p. 40).

The fall-cone liquid limit. — The liquid limit of the soil is defined as the water ratio at which the penetration of the cone in a fall-cone apparatus is 10 mm (Broms *et al.* 1975). At the liquid limit the shear strength is 1.5–2.0 kPa.

The consistency of cohesive soils changes with the water ratio, from liquid to plastic, semi-solid, and solid as the water ratio gradually declines.

Percussion liquid limit. — The percussion liquid limit (w_L) was determined by means of Casagrande's device (Karlsson 1977). Concerning performance the determination of the liquid limit with the fall-cone apparatus is less influenced by minor variations than the corresponding test with Casagrande's device. Moreover, the former test is easier to handle.

Plastic limit. — The plastic limit (w_p) is defined as the lowest water content at which a remoulded soil sample can be rolled to a 3 mm thick thread without crumbling (Karlsson *op. cit.*).

The consistence of a soil will be desingated in terms of the liquid limit, see Table 1.

Table *1.* Classification of clays by means of the plasticity index, I_p, and the liquid limit, w_L (after Karlsson 1977).

Designation	Plasticity index, I_p %	Liquid limit, w_L %
Low-plastic	<10	<30
Medium-plastic	10–25	30–50
High-plastic	>25	>50

For non-plastic soils $I_p = 0$.

Plasticity index. — The plasticity index (I_p) denotes the difference between the water content at the liquid and the plastic limit, respectively:

$$I_p = w_L - w_p \qquad \text{(Karlsson } op.\ cit.\text{)}$$

The plasticity index, I_p, is numerically equal to the change in the water ratio of the remoulded sample which is

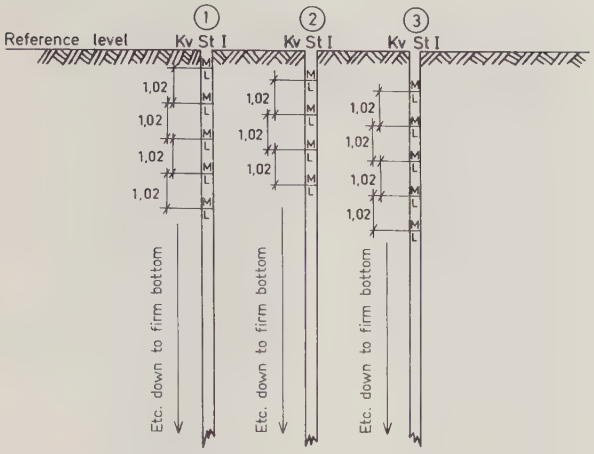

Fig. 5. The sampling method with overlaps between the tubes.

Fig. 6. Ground-plan of the field investigations at Dynäs.

necessary to alter the consistency from liquid to semi-solid. The plasticity index of a soil gives an idea of such factors as compressibility and shear strength, for a high index often implies high compressibility and low shear strenght of the soil. The index of a fine-grained organic sediment is low when little clay is present.

As the plasticity index depends on the content of clay and the type of clay mineral (Broms 1972) it is also used in the classification of soils (Table 1).

Liquidity index. — The liquidity index (I_L) is defined as follows (Karlsson *op. cit.*):

$$I_L = \frac{w - w_p}{I_p}$$

where w = water ratio of the sample
w_p = plastic limit
I_p = plasticity index

Table 2. The relationship between the liquidity index, I_L, and the consistency of a remoulded soil, according to the Laboratory Committee and the Swedish Geotechnical Society (Karlsson 1977).

Water content in relation to w_p and w_L	Liquidity index, I_L	Consistency of a remoulded soil
$w < w_p$	$I_L < 0$	Solid — semi — solid
$w = w_p$	$I_L = 0$	
$w_p < w < w_L$	$0 < I_L < 1$	Plastic
$w = w_L$	$I_L = 1$	
$w > w_L$	$I_L > 1$	Semi — liquid — liquid

For normally consolidated Swedish clays the liquidity index varies between 0.8 and 1.5. For quick clay it can reach 2.0 or higher. The liquidity index decreases with increasing consolidation pressure and can be as low as zero in the dry crust (Broms 1972). The index is a measure of the consistency of a soil in a remoulded state and is also used as a measure of the sensitivity of the sample. The relationship between the consistency of a remoulded sample and the liquidity index is shown in Table 2.

Undrained shear strength, unconfined compression test. — The undrained shear strength was estimated by means of the unconfined compression test (Geonor G 250, Hansbo 1975), the fall-cone tests and the vane apparatus test (apparatus constructed by Jonell-Nilcon, Broms 1972). The unconfined compression test is usually performed only on cohesive soils as a change in the water ratio of the sample will influence the results.

The shear strength according to the unconfined compression test for normal consolidated clays usually agrees with the result of *inter alia* the fall-cone test or the vane-apparatus test. For overconsolidated clays the shear strength is affected to a great extent by the normal system of fissures in the soil. For boulder clay the shear strength according to the unconfined compression test is often only a third or a fourth of the value given by the vane-apparatus test (Broms 1976).

Undrained shear strength, fall cone stest. — The undrained shear strength of cohesive soils (clay, dy, gyttja) and fine-grained intermediate types of soil (silt) was estimated via the fall-cone test by applying the point of an iron cone to the upper surface of a sample. The cone was then allowed to fall and the depth of penetration measured.

The shear strength was originally expressed in numbers, determined by the fall-cone test and designated H_1, H_2 and H_3 (The Geotechnical Commision of the Swedish State

Railways 1914—1922, 1922). H_1 denotes remoulded clay, the H_2 partly disturbed clay and H_3 undisturbed clay.

Comparisons between unconfined compression tests, punching tests and land-slides yielded the following relationships between undrained shear strength τ_{fu}, in kPa, and H_3 as suggested by SGI: $\tau_{fu} = 10\ H_3/(36 + 0.064\ H_3)$ (Broms 1972).

When new piston samplers were developed and the quality of the samples improved these expressions, however, gave too high values of shear strength. The values proposed by The Committee on Piston Sampling of the Swedish Geotechnical Society (in Kallstenius & Hallén 1963) have been adapted to the quality of samples from standard piston sampling (St I and St II). Nevertheless, an uncertainty arises in interpreting small cone penetrations (2—3 mm) as small variations in the performance of the test may greatly influence the results.

For measurements of the undrained shear strength of the loose to firm cohesive material *in situ* the field-vane apparatus was used (Broms 1972). However, the results of the tests sometimes show shear strength values of a normally consolidated clay which are much higher along a horizontal than along a vertical plane (anisotropic soil) (Broms *op. cit*). The opposite condition is apparently valid for overconsolidated clays. Because of such differences the shear strength obtained with the vane-apparatus test may greatly diverge from the average shear strength of the material (Broms *op. cit.*).

The field-vane apparatus test is also used for estimating the relative density of friction and intermediate types of soils (Broms *op. cit.*). Minor changes in the relative density will cause major variations in estimated shear strength. There is thus a great uncertainty in the interpretation of the results.

Sensitivity. — The ratio between the undrained shear strength of the cohesive soil in undisturbed, τ_{fu}, and in remoulded condition, τ_r, is called sensitivity ($S_t = \tau_{fu}/\tau_r$). As a rule the sensitivity is determined via the fall-cone test or with a field-vane apparatus. The sensitivity of Swedish clays normally varies between 10 and 30. The designation "quick clay" is used when the sensitivity as measured by the field-vane apparatus exceeds 30 (Skempton *et al.* 1950, Skempton 1952, the Laboratory Committee of the Swedish Geotechnical Society, report in preparation), the corresponding value for the fall-cone test being 50. The valley of River Göta älv contains clays with sensitivities up to 500—700 (Broms 1972). The remoulded shear strength, τ_r, is determined on samples which have been remoulded manually.

However, τ_r measured by field-vane tests, may be influenced by changes in the water ratio in the thin layers where the shearing appears. The friction along the vane apparatus rod will then influence the estimated torque, especially when the sensitivity is high (cf. Broms 1972). Accordingly the calculated value of sensitivity will fall far short of that given by, *e.g.*, the fall-cone apparatus when $S_t = 10$.

The clays can be classified with respect to their susceptibility to remoulding by means of the sensitivity, S_t. The classificaiton is shown in Table 3.

Furthermore, a clay is adjusted a quick clay if the sensitivity, $S_t > 50$ and the penetration of a 60 g and 60° fall cone exceeds 20 mm in the remoulded clay. This classification in terms of the sensitivity, S_t, adheres in the main to international standards.

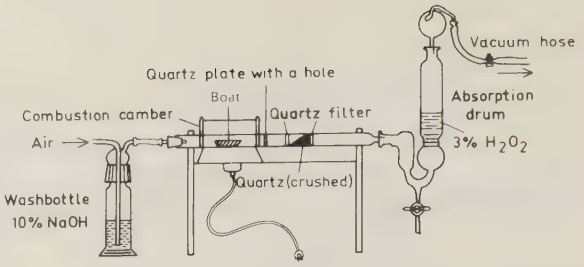

Fig. 7. Apparatus for sulphur determinations (modified from Grote & Krekeler, 1968).

Table 3. Clay classification regarding susceptibility to remoulding (after the Laboratory Committee of the Swedish Geotechnical Society, report in preparation).

Designation	Sensitivity, S_t
Low sensitive	<8
Medium sensitive	8—30
High sensitive	>30
Quick clay	>50

This method of determining the susceptibility to disturbance of a clay, however, does not take into account the energy needed to remould it. In a method proposed by Söderblom (1973), the energy for disturbance is constant and the suspectibility expressed as the rapidity of a soil. However, as by definition quick clays have a remoulded shear strength of <0.5 kPa and a sensitivity >50, penetration of the 10 g/60° cone > about 7,5 mm (Karlsson 1977).

Ignition loss. — The content of organic material in the samples was determined by measuring the loss of weight of a sample which was first dried at 105°C to constant weight and then heated in a combustion chamber at 550°C for 4 to 5 h (Jackson 1958). The organic material in the samples is thereby consumed. As a result of heating the samples to a maximum 550°C the risk is slight that the water bound to the mineral grains will vanish during the ignition (Skempton & Petley 1970). The ignition loss is reported in per cent of the dried mass of the soil. No corrections for carbon dioxide and content of clay were performed.

Sulphur content. — Determinations of sulphur were performed with the quartz tube method (Grote & Krekeler 1968).

One gram of a sample dried at 105°C is placed in a porcelain-boat and placed in the quartz tube (Fig. 7). The sample is heated for 15 minutes. The derived gas is conducted through an absorption drum with hydrogen peroxide. The absorption liquid is poured into an Erlenmeyer flask; 5—6 drops methyl red (red colour) are added. The liquid is then titrated with 0.1 N NaOH until it turns yellow. For determination of eventual background values from sulphur in the air, a blank determination was made. The boat used was then excluded.

On heating, absorption and titration the following will happen: sulphur and oxygen will form sulphur dioxide which is absorbed by hydrogen peroxide to form sulphuric acid. Sulphuric acid and sodium hydroxide will form

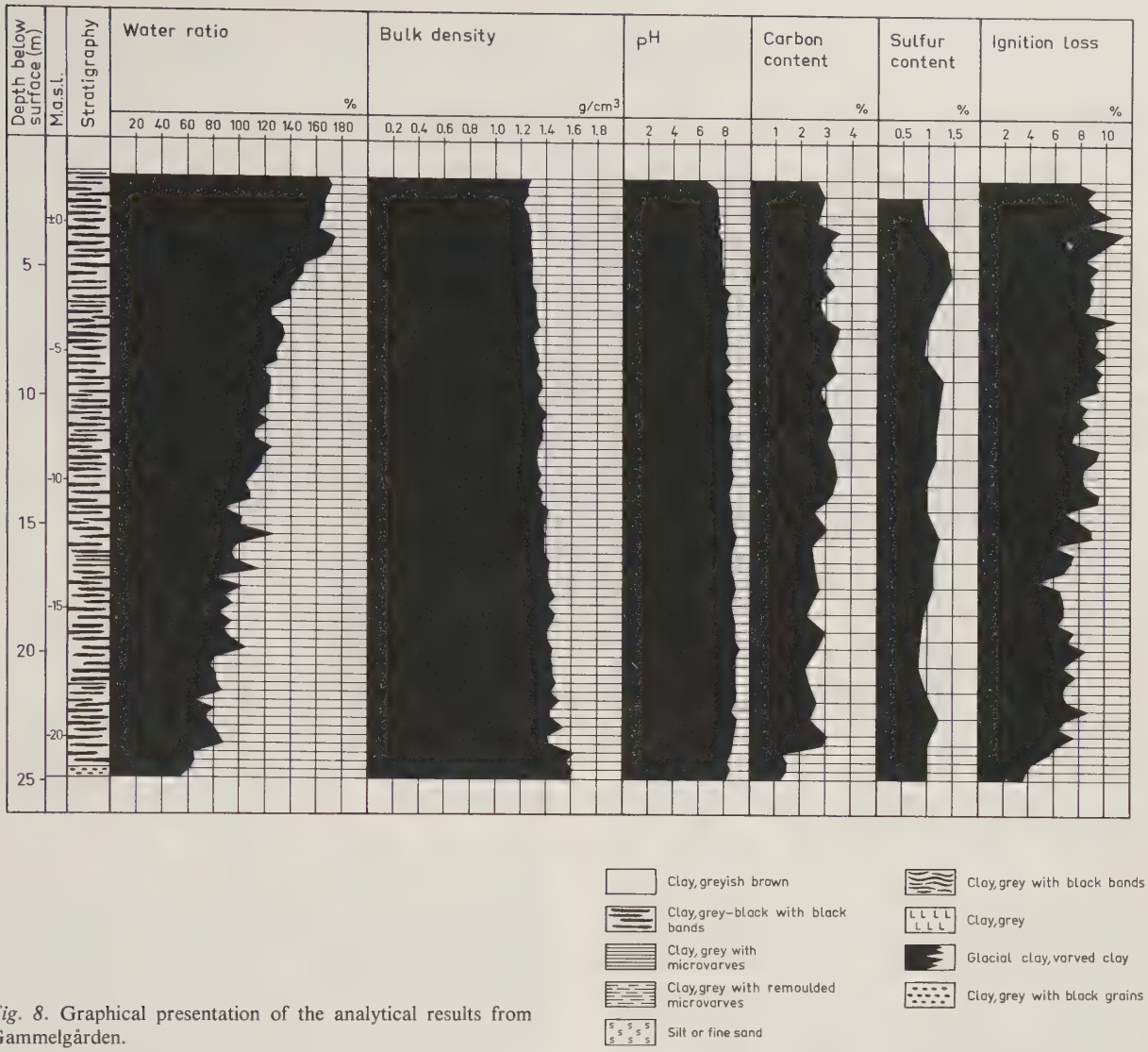

Fig. 8. Graphical presentation of the analytical results from Gammelgården.

sodium hydrogen sulphate and water. In order to assess interference by carbon residues of combustion were mixed with known amounts of clean sulphur and carbon. Moreover clean sulphur was burnt. These samples were then analysed using the quartz-tube method. There are no indications that the presence of carbon will influence the results.

Carbon content. — The determinations were carried out with two different methods, a dry combustion (Reilen & Weinbrenner 1954) and wet combustion (Jansson & Waldmaa 1961). The wet combustion method is the more reliable. In the dry combustion method contaminants, such as sulphur, may affect the results.

pH. — The hydrogen ion activity, pH, was determined on fresh samples, suspended in water in the proportion 1:1 (cf. Jackson 1958). The determination was performed by a pH meter Metrohm 396 and a combination electrode. The instrument was continuously calibrated with a buffer liquid for the range of measurement at which the determination was performed.

Eh. — The determination of Eh was carried out in the same samples as the above, immediately after sampling. The measurement was made directly in the sediment by means of two electrodes (calomel and platinum) over a salt bridge. The reading was taken at stability, after about four min. (Hallberg 1968, 1971, Whitfield 1969).

Total contents of elements. — The total contents of an element in a soil sample comprises both lattice-bound and adsorbed and dissolved—in the pore water—amounts.

Total contents of the following elements were determined: Al, Ca, Fe, K, Mg, Na, P, Si, Ti, Zn, and Cu. With the exception of Zn and Cu, the contents are given as the percentages of the respective oxides. The pretreatment and analytical procedure follow Shapiro & Brannock (1962, see especially Fig. 1 p. A3). The elements Ca, Mg, Fe, Cu, and Zn, however, were determined by an atomic absorption spectrophotometer (Varian 1200).

Exchangeable ions. — In order to determine the exchangeable ions adjusted of importance for the technical properties of the soil, the samples were leached with an ammonium-acetate solution. The analytical procedure follows Jackson (1958) with later modification (see Ericsson 1973). This implies that the contents indicated for the exchangeable ions comprise also the ions dissolved in

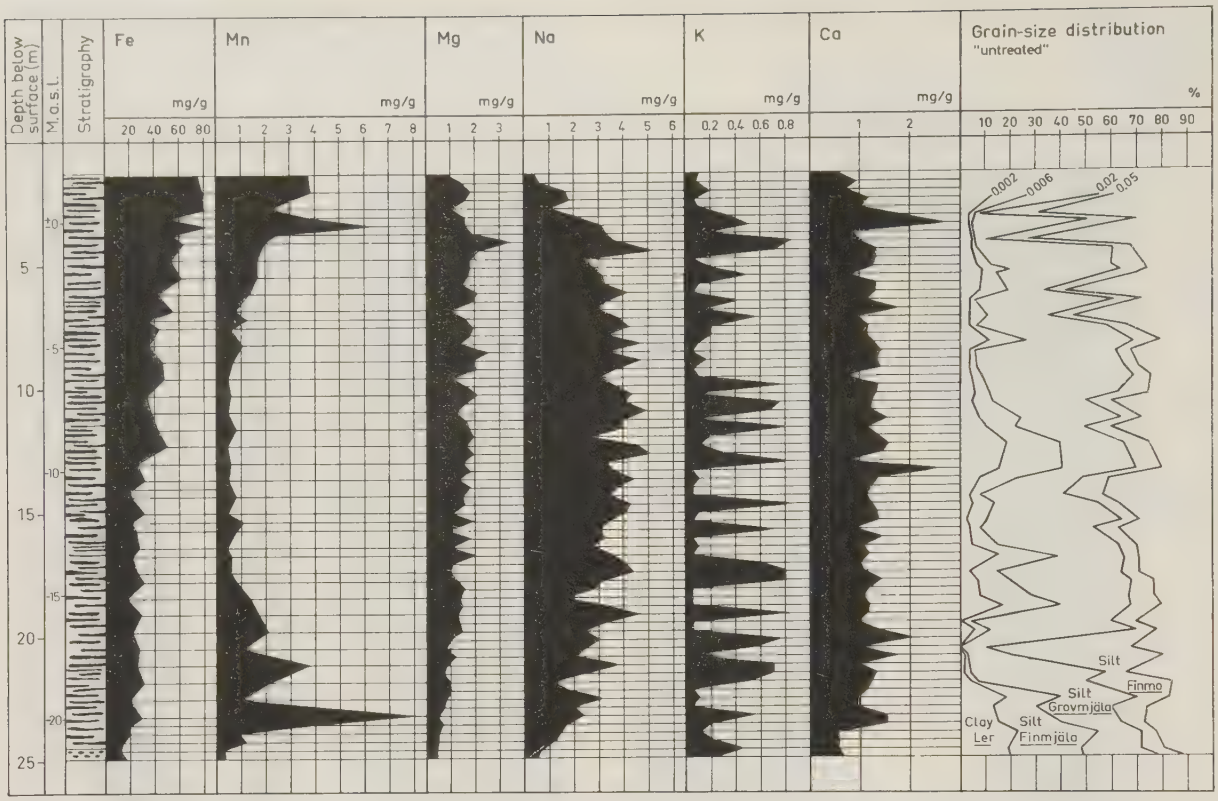

Fig. 9. Graphical presentation of the analytical results from Gammelgården.

the interstitial water (Løken 1970). An atomic absorption spectrophotometer was used for the analyses.

Extractable elements. – Extraction of Fe and Mn was performed in the samples from the site Gammelgården. The extraction was made at room temperature using hydrochloric acid (cf. Jackson 1958, Bear 1964, Ståhlberg 1964, Rose 1974, Petersen 1976). Fifty ml M hydrochloric acid were added to 1–1.5 g of soil, dried at 105°C and mortared. The suspension was agitated for one hour and centrifuged at 2,000 rpm. The clear supernatant liquid was filtered into a 100 ml volumetric flask. The extraction was repeated with 25 ml M hydrochloric acid. The extract was diluted to 100 ml with M hydrochloric acid. Both the ions in the interstitial water and those adsorbed to the organic matter and the clay minerals, as well as those ions coprecipitated in various inorganic and organic gels, are thereby released. Furthermore, as the soil was dried at 105°C, the metastable sulphides mackinawite and greigite (cf. p. 5) will be oxidized to sulphate, contributing to the extraction. Furthermore, the oxides and hydroxides of Fe and Mn would seem to be totally dissolved.

According to Papunen (1968) the iron extracted may be derived on high degree from the hydroxides and sheet silicates, particularly chlorites. In his X-ray investigation of sulphide-rich sediments from the province of Ångermanland, Modig (1967) identified dioctahedral illite and vermiculite, and iron-rich chlorite.

Pollen analysis. –The age was determined via pollen analysis on a core extracted by Foil Sampler at Rödäng. Every fifth centimetre of the core from 1.62 metres below the ground surface down to 14.17 metres was sampled. So far every fifth sample is examined for content of tree pollen. The treatment of the samples for pollen analysis follows Troels-Smith's (1955) modification of Erdtman's method (Erdtman 1936). All samples were treated with hydrofluoric acid as described by Jørgensen (1963). The slides were stained with basic fuchsin and sealed with wax and shellac. About 300 pollen grains were counted in each sample. Values less than one per cent were excluded from the pollen diagram.

Statistical treatment

Correlation and significance tests. – All data describing physical and chemical properties of the sediments were treated statistically by means of a computer program (Statistical Package for the Social Sciences, SPSS, Nie *et al.*, 1975). The values were manually arranged according to the stratigraphical pattern. This implies that they were processed in groups. The Pearson correlation program from the SPSS system was chosen. Thus the mean, the standard deviation, the Pearson correlation coefficients, and the level of significance were calculated. The significance test was performed using the Student's t with N-2 degrees of freedom for the computed quantity:

$$t = r\left[\frac{N-2_2}{1-r^2}\right]^{1/2}$$

where t = test quantity, r = correlation coefficient.

In the case of the Pearsson correlation coefficient miss-

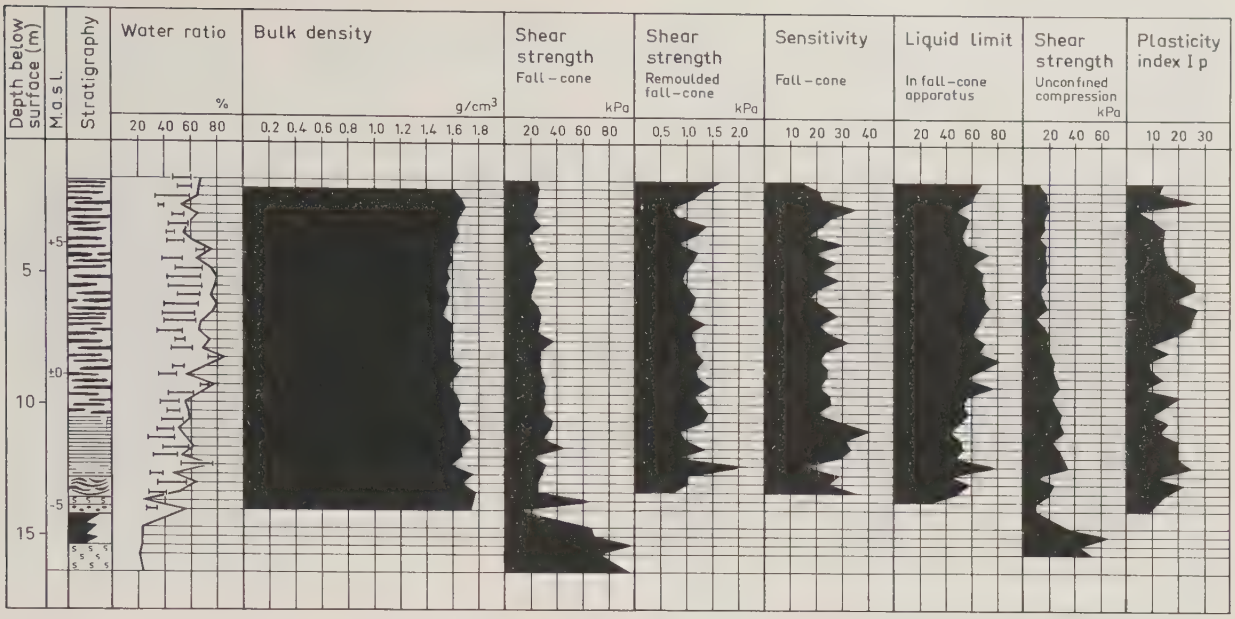

Fig. 10. Graphical presentation of the analytical results from Rödäng.

ing values were pair-wise deleted. When interpreting the results of the Pearson correlation test only those coefficients were used which correspond to a significance level below or equal to five per cent.

Regression tests. — Regression tests were performed (Davis 1973) for the purpose of studying the relationship between the individual parameters. The correlation and regression tests on data from whole bed sequences or parts thereof may be misleading if used to interpret the environmental conditions. A thick sequence, several metres—in some cases > 20 metres—results from deposition through many centuries or millennia. Even if the sediment seems uniform it contains irregularities, *e.g.* bands, faults, and overflow deposits. Obviously these phenomena, isolated or interacting, form an inhomogeneous sediment sequence. The sampling interval, 17, 34, and sometimes 68 cm represents a period of deposition between 50 and 400 years. Obviously a correlation or regression test on such a quantity of values treated mathematically/statistically as true figures, can serve to reveal possible similarities or dissimilarities. Tests reflecting the secondary environment within the sediment, *e.g.* pH and Eh, and of course tests demonstrating the actual shear strength properties, soil-water conditions and rate of compaction should be tolerably reliable.

Time-trend analysis. — As parts of the curves fluctuate strongly, data were processed by time-trend analysis (Davis 1973). Moving averages were calculated. This involves smoothing, reducing the variance of the original sequence—the longer the interval, the greater the reduction. The method needs careful interpretation; a shift of peaks and troughs may be the most serious consequence of the smoothing. This is particularly obvious if the original curve contains asymmetric peaks. Time-trend analysis was used in interpreting the curves of carbon content, ignition loss, sodium, potassium, and calcium content from Gammelgården.

Results

Gammelgården

Stratigraphy. — Table 4 shows the stratigraphy of the sediment core.

Table 4. Gammelgården, stratigraphical description of the sediment core.

Depth below surface, metres	Description
0 — 1.25	Dry crust, fairly red-brown
1.25— 2.58	Grey-black clay with indications of black sulphide bands, 0.5 cm thick, at intervals of about 1 cm
2.58—10.12	Homogeneous, black, porous sediment, lubricious, immediately after dividing; after a while a faint indication of banding as above
10.12—10.41	Homogeneous, black sediment, disintegrating into more or less cubic aggreagates
10.41—11.43	Black sediment with indications of banding as above
11.43—11.62	Homogeneous black sediment, brittle in friable structure
11.62—17.00	Homogeneous black and shiny sediment with indication of banding
17.00—24.18	The sediment is black with distinct bands some 3 mm wide at 5 mm intervals
24.18—24.44	As above but somewhat more grey
24.44—25.07	Distinctly banded sediment, in the upper part bands 1 mm thick downwards 7—8 mm; in the lowest part the sediment is speckled.

Grain-size distribution. — The clay content approaches 12 % about 2 m below surface (Fig. 9). It then fluctuates between 5 and 10 % down to about 10.5 m, whereupon the curve rises to a maximum of 18 % at 12.3 m.

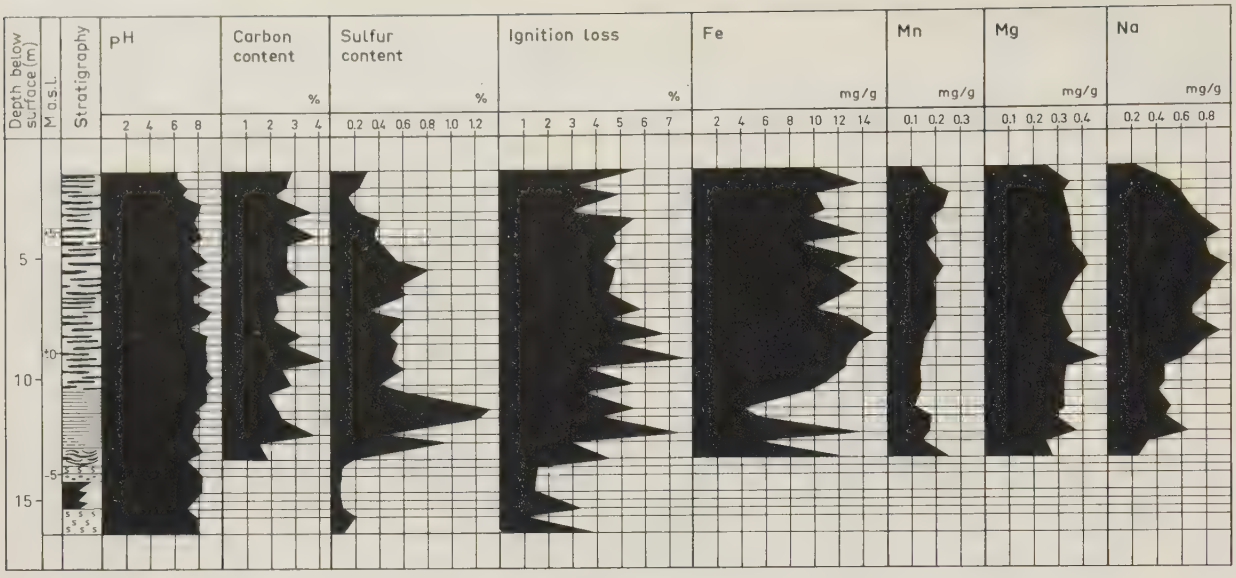

Fig. 11. Graphical presentation of the analytical results from Rödäng.

Down to 20.3 m the clay content curve fluctuates from 0 to 16 %. Between 20.3 and 24.9 m it increases to just above 20 %. The fine silt curve tends to follow the clay curve. The modal fraction of the grain-size distribution diagram is the coarse silt. Its curve does not follow the clay curve as closely as the fine silt, except for the last 6 m. The curve of the coarse silt fraction is very similar to that of the medium silt. The fine silt varies from zero to approximately 30 %, the medium silt between 3 % and about 60 % and the coarse silt between 5 % and roughly 55 %.

Water ratio. — The water ratio of the sediments in the bed sequence was determined from about 1.6 m below the ground surface down to 24.9 m (Fig. 8). Analyses were made every 34 cm.

The values of the diagram tend to divide the bed sequence into three layers. The uppermost, from about 1.4 to 6.5 m down, shows an almost linear development. The water-ratio values range from 170 % to about 130 % from top to bottom. Between 6.5 and about 20.5 m below surface the curve is still linear, from 130 % to about 80 %, with a steeper gradient. From 20.5 to about 24.9 m the values decrease linearly from 80 % to about 50 %; the gradient is somewhat gentler.

Bulk density. — The bulk density was determined in the same samples as the water ratio, *i.e.* every 34 cm (Fig. 8). The values show an almost linear increase from 1.3 g/cm^3 about 1.4 m below surface to 1.4 g/cm^3 at 23.4 m. Between 23.4 and 24.9 m the bulk density approaches 1.6 g/cm^3.

pH. — The pH values (Fig. 8) are fairly constant throughout varying from just over 7 to about 8.5. The sample from 1.4 m in the dry crust has the lowest value, about 6.5. Then between 1.7 and 5.5 m the values increase from about 7.5 to about 8. From 5.5 to 22 m the pH values increase rather linearly from about 8 to 9, and fall back to 8 between 22 and 24.9 m.

Ignition loss. — The loss on ignition was determined every 34 cm throughout the section (Fig. 8). High single values are found up to about 11.4 %. The uppermost sample was determined to 7.8 %. At about 3.4 m the curve reaches a peak of 11.4 %, then falls to about 8 % at 6.5 m. Down to 9.5 m there are slight variations round 9 %. From 9.5 metres the curve fluctuates fairly strongly but shows a significant decline from about 9 % to 5 % at 17 m. In the interval between 17 and 23 metres the curve is fluctuating, but the values increase from about 5 % to about 7 %. From 23 down to 24.9 metres the values decrease more or less constantly from 7 % to 3.6 %.

Carbon content. — For want of material the carbon content (Fig. 8) could not be determined as exactly as the water ratio. It was sometimes determined only every 68 cm (cf. diagram). The carbon content increases from about 2.6 %, 1.4 m below surface, to 3.4 % at a depth of about 9 m. In the section 9 to 23 m the values decrease from 3.4 % to about 2.5 % and between 23 and 24.9 m from 2.5 % to 1.2 %.

Sulphur content. — The sulphur content was generally determined every 68 cm in the sequence (Fig. 8). The values range from about 0.8 % 2 m below surface, to 1.4 %, at about 5 m down. In the interval 5 to 8 m the values decrease from 1.4 % to 0.9 %. At 9.2 m there is a local maximum of 1.6 %, and the curve then decreases to 0.9 % at a depth of 13.3 m. Between 13.3 and 20.3 m the curve peaks at 15.3 m, reaching 1.3 %. At 22.4 metres there is another maximum of 1.3 %. In the last 1.4 m of the sequence the sulphur content is constant at 1.0 %.

Extractable iron. — The iron content was generally determined every 68 cm in the sequence (Fig. 9). It constitutes 70—80 mg/g about 2 m below surface, and then declines to about 40 mg/g near 6.5 m. Between 6.5 and about 14 m the decrease approaches 20 mg/g with local maxima at 9 and 12 m, 48 and 50 mg/g respectively. In the interval between 14 and 23 m the iron content remains fairly constant at 20—30 mg/g. From 23 to 24.9 metres it falls from 30 mg/g to 16 mg/g.

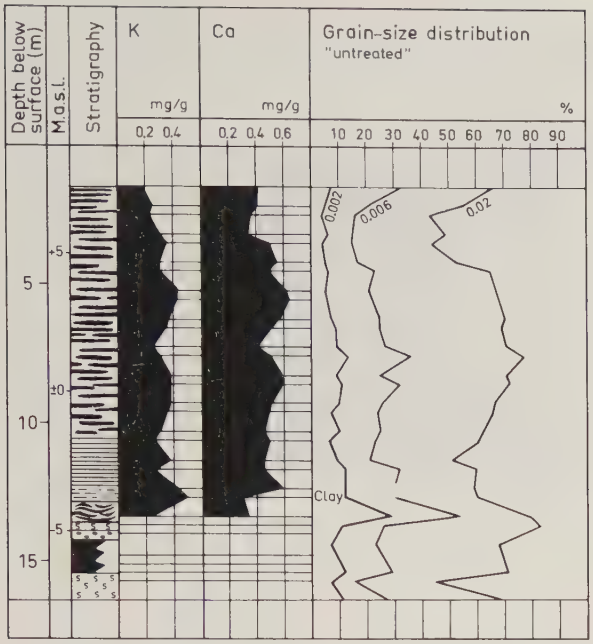

Fig. 12. Graphical presentation of the analytical results from Rödäng.

Extractable manganese. — The manganese content was determined in the same samples as the iron content, *i.e.* every 68 cm throughout the section (Fig. 9). In the case of uppermost 17.5 m the similarity to the iron curve is striking. Both have maxima 3.3 m below surface. Apart from this peak the manganese values decrease from about 3.5 mg/g at 1.4 m to 0.7 mg/g at about 6.5 m. Between about 6.5 and 17.5 m the manganese content remains comparatively constant, fluctuating between 0.5 mg/g and about 1 mg/g. At 17.5 metres it suddenly rises from about 0.5 mg/g to a distinct peak of 7.8 mg/g at about 23 m. The increase is interrupted by two minima of 1 mg/g, at 20.5 and 22.5 m. From about 23 m the values decrease to about 0.4 mg/g at 24.9 m.

Exchangeable magnesium. — The magnesium content was determined every 34 cm throughout the section (Fig. 9). It fluctuates between 1 and 2 mg/g in the interval 1.4 to about 17.5 metres, apart from local peaks of 3.5 and 2.5 mg/g, respectively, at 4 and 9.5 m. From about 18 to 24.9 m the values decrease from about 1.5 mg/g to about 0.5 mg/g.

Exchangeable sodium. — The sodium content was assessed at 34 cm intervals throughout the sequence (Fig. 9). It too fluctuates; nevertheless the curve resembles a parabola, reaching its maximum at about 12 m. The values increase from 0,5 mg/g at 1.4 m to about 4.5 mg/g at 12 m, with a distinct peak of 5 mg/g at about 4.5 m. At about 12 m the curve enters a decline from about 4.5 mg/g to about 0.5 mg/g at 24.9 m.

Exchangeable potassium. — The potassium content was determined every 34 cm throughout the section (Fig. 9). No pronounced pattern of distribution can be seen. The curve fluctuates strongly between 0.1 mg/g and about 0.85 mg/g allthrough the sequence.

Exchangeable calcium. — The calcium content was determined every 34 cm throughout the section (Fig. 9). The uppermost part shows an increase from about 0.5 mg/g at 1.4 m to 1.2 mg/g at about 4 m. Between 4 and about 21.5 m the curve fluctuates between 0.8 mg/g and about 1.5 mg/g.

Five distinct peaks are visible, at 4.5, 6.8, 13.3, 20, and 21.3 m, with calcium contents of 2.7, 1.7, 2.5, 2.0, and 1.6 mg/g. From 21.5 to 24.9 m the values fall from about 1.3 mg/g to about 0.5 mg/g, with a maximum of about 1.5 mg/g at 23.3 m.

Rödäng

Stratigraphy. — Table 5 shows the stratigraphy of the sediment core.

Table 5. Rödäng, stratigraphical description of the sediment core.

Depth below surface, metres	Description
0 — 1.50	Dry crust, grey clay
1.50—10.50	Clay, black, with micro-varves, thinner upwards. The clay becomes lighter downwards. A black banding is clearly visible, the bands about one cm wide at intervals of one to three cm
10.50—12.35	Clay, grey, with micro-varves
12.35—12.79	Clay, black, with micro-varves, downwards lighter with remoulded micro-varves
12.79—13.52	Clay, grey, with black bands, dark on top, lighter downwards
13.52—13.93	Silt, grey, fluid
13.93—14.25	Clay, grey, with black grains, fluid
14.25—15.40	Clay, grey, glacial, varved
15.40—	Fine sand

Grain-size distribution. — Grain-size analyses were performed alternately every 34 and 68 cm in the core from 1.4 to 16.3 m (Fig. 12). The clay content is about 7 % at 1.4 m below surface. It then shows a wavering increase to about 12 % at 7.5 m. From 7.5 to 10.5 m a fluctuating decrease to 6 % appears. The curve then reaches a peak of 28 % at 13.2 m. Between 13.2 and 14.3 m the clay content declines to 7 % and between 14.3 and 16.3 m it represents 10 ± 3 %. The fine silt curve resembles that of the clay content throughout the section. The values vary between approximately 8 % and 25 % with maxima and minima mostly coinciding with those of the clay content. The coarse silt fraction varies between about 25 % and 45 %. The curve is very similar to those of the fine silt and the clay content.

Water ratio. — The water ratio was determined every 34 cm throughout the bed sequence (Fig. 10). It ranges between 20 and 86 %. The values decrease slightly from 67 % at 1.4 m to 54 % at 3.5 m. An increase ensues with a peak at about 6 m with a water ratio of 80 %. The water ratio then hesitantly declines to 11 m where the water ratio is 52 %. After climbing to a peak of about 70 % at 12.5 m it falls toward 20 % at 13.5 m. There is a local peak of

56 % at about 14 m whereupon the curve remains constant at 20 % down to 16,4 m.

Bulk density. — The bulk density was determined in the same sample as the water ratio down to 14 m below surface (Fig. 10). At 1.7 m the bulk density is 1.6 g/cm^3, then rises to 1.7 g/cm^3 at 2.4 m. Between 2.4 and 6.5 m it gradually descends from 1.7 g/cm^3 to about 1.5 g/cm^3. In the interval 6.5 to 11.3 m the values rise, although less evenly than in the overlying layer. The bulk density increases from about 1.5 g/cm^3 to 1.7 g/cm^3. Then between 11.3 and 12.3 metres the values fall from 1.7 g/cm^3 to 1.6 g/cm^3. In the lowest layer the values fluctuate round 1.7 g/cm^3.

Undrained shear strength, fall-cone test. — Fall-cone tests of the shear strength were made in the same samples as above throughout the bed sequence (Fig. 10). The shear strength is 25 kPa at 1.4 m; the curve then drops to about 20 kPa at 3.5 m. Thereafter the shear strength slightly increases, although fluctuating, down to 11.6 m where it approaches 40 kPa. From 11.6 m the curve fluctuates strongly with an incipient decline to 14 m. At 13.6 m a local peak of about 64 kPa is found. In the interval 14 to 16.7 m the curve tends to rise, the highest value being approximately 87 kPa.

Remoulded shear strength, fall-cone test. — The remoulded shear strength was determined in the same samples as above down to 13.3 m (Fig. 10). At 1.4 m the remoulded shear strength approaches 1.6 kPa, then declines to 0.7 kPa at 2.4 m. At 3.1 metres a peak of about 1.3 kPa appears. The curve then fluctuates with a rising tendency from just below 1 kPa to 1.3 kPa at 10.2 m. In the interval 10.2 to 13.3 m the curve fluctuates strongly with a tendency to decrease. There are two pronounced minima of 0.9 kPa at 11 and 12 m. A distinct peak of about 2 kPa occurs at 12.3 m.

Sensitivity, fall-cone test. — The sensitivity was determined in these same samples down to 13.3 m (Fig. 10). The values fluctuate strongly around 20—30 throughout the profile. There are, however, three distinct peaks with sensitivity values above 30, even as high as 40. At 2.4 m the sensitivity is 34, at 11 m 40 and at 13.3 m 35.

Fall-cone liquid limit. — The liquid limit is calculated in the same samples as above down to 13.6 m below surface (Fig. 10). It varies between approximately 30 and 80. At 1.4 m the liquid limit approaches 68; it then decreases to about 52 at 3.5 m. From there to about 6 m the curve descends towards 70. The values then fall to 60 at 7.2 m. A maximum of 80 occurs at 8.3 m. In the interval 8.3 to 11 m there is a fluctuating decrease to about 45. Between 11 and 13.6 m a maximum of 80 appears at 12.3 m; the curve then declines to about 30.

Undrained shear strength, unconfined compression test. — Tests were made on the samples as above all through the bed sequence (Fig. 10). The uppermost layer, 1.4 to about 7 m, presents fairly constant shear-strength values of 17—18 kPa. At 6.5 m there is a minimum of about 10 kPa. From 7 to 12.3 m the shear strength increases from 18 kPa to about 34 kPa. In the interval 12.3 to 13.6 m it plunges to about 10 kPa. From 13.6 m the curve drops, with a maximum of 64 kPa at 15 metres.

Plasticity index. — The plasticity index was calculated for the samples analysed down to 14 m (Fig. 10). At 1.4 m it is 14, at 3 m 25 and at 3.5 m 5. From 3.5 to 6.2 m the values rise to 27, followed by a drop to about 10 at 7.5 m. Between 7.5 and 12.5 m there is a strongly fluctuating increase to about 25, followed by a drop from 12.5 to 14 m.

pH. — The pH values were determined almost every 34 cm throughout (Fig. 11). They range from 6 to 9. At 1.4 m the pH is about 6; it then increases to about 8 at 2.7 m. In the interval 2.7 to 11 m the pH values show a fluctuating increase from 8 to 8.6, with a maximum of 9 at 9.9 m. Between 11 and 16.3 m the pH values fluctuate between 8.6 and 7.9 with a decreasing tendency.

Ignition loss. — The loss on ignition (Fig. 11) was calculated in the same samples as the sulphur content. The values fluctuate widely throughout the sequence. At 1.4 m the ignition loss is 5.5 %; it then oscillates down to about 3 % at 3 m. From 5.5 % at 3.5 m it decreases to 4.5 % at 6.5 m. Between 6.5 and 9.3 m it has a fluctuating increase to 7.6 %. The values then decline, and between 9.5 and 11.5 m the ignition loss fluctuates strongly around 4.5 $\pm$ 1 %. A peak maximum of 7.3 % occurs at 12.3 m. From 12.3 to 14.6 m the curve meanders down to 1.4 %. The lowest layer, 14.6—16.3 m, shows an increase to 3.8 % interrupted, however, by a single minimum of 1 % at 15.7 m below surface.

Carbon content. — The carbon content was determined at 34 or 68 cm alternately down to 13.3 m (Fig. 11). The carbon content fluctuates greatly throughout. From 2.9 % at 1.4 m it decreases to 2.2 % at 2.5 m. Between 2.5 and 6.2 m the curve fluctuates strongly around 3 % with a minimum at 2.5 % and a maximum at 3.8 %. Between 6.5 and 7.5 m the values approach 2.2 %. From 7.5 to 9.3 m the curve drops to about 4.2 %. Then, between 9.3 and 10.5 m, the values decrease to 1.8 %, and, from 10.5 to 12.3 m only to rise again to 3.8 %. The lowest layer, down to 13.3 m, shows a decline to 1.8 %.

Sulphur content. — The sulphur content was determined at alternately every 34 or 68 cm all through the bed sequence (Fig. 11). At 1.4 m it is 0.3 %; from there it decreases to 1.4 % at 3.4 m. Between 3.4 and 5.5 m there is a rise to 0.8 %. From 5.5 to 7.2 m the values decrease to about 0.3 %. Between 7.2 and 10.2 m the sulphur content fluctuates around 0.5 % $\pm$ 0.1 %. At 10.2 to 11.5 m a steep increase, to 1.3 % occurs. In the interval 11.5—13.5 m the sulphur content decreases to 0.08 %. The lowest stratum, 13.5—16 m, is rather constant, at 0.08 % appart from a single peak of 0.2 % at 15.7 metres.

Exchangeable iron. — The iron content was determined in the same samples as above down to 13.3 m below surface (Fig. 11). It fluctuates greatly throughout the section. At 1.4 m it is 10.4 mg/g and at 2.1 metres 13.5 mg/g. Then, from 2.1 to 3.4 m, the curve drops to 9.4 mg/g. Between 3.4 and 6.2 m the values show a rising trend, although fluctuating; at 6.2 m the iron content is 13.6 mg/g. From 6.2 to 7.2 m the curve descends to 10 mg/g while at 7.2 to 8.3 metres it climbs to 14.8 mg/g. Between 8.3 and 11.2 m the curve plunges to about 4 mg/g. Below 11.2 m only four analyses were performed, two showing peaks of 13.6 mg/g and 12 mg/g at 12.3 and 13.3 m. These maxima are intersected by a through of about 5 mg/g at 13.6 m below surface.

Exchangeable manganese. — The manganese content was determined in the same samples as the iron down to 13.3 m

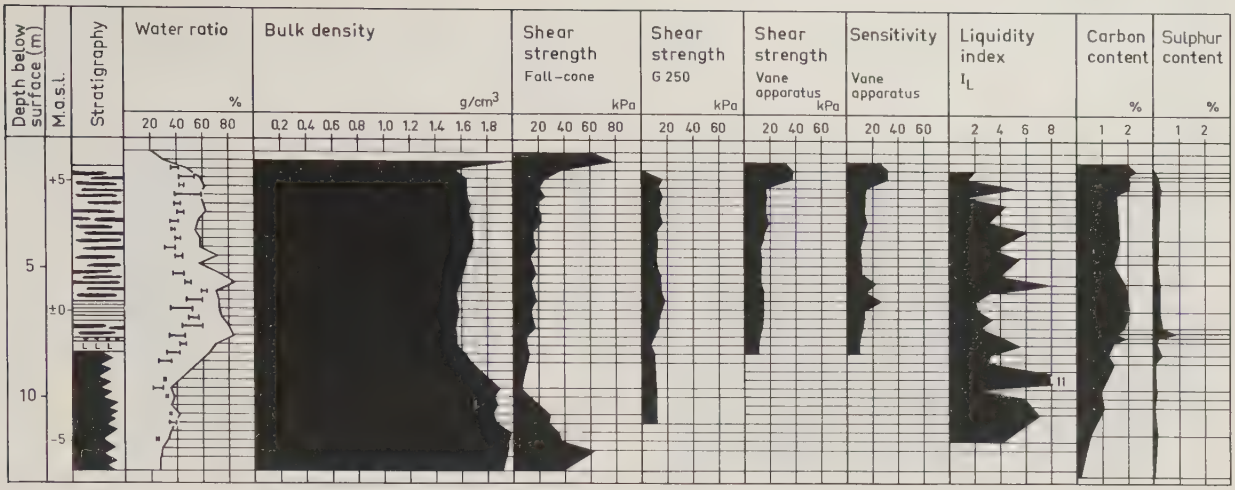

Fig. 13. Graphical presentation of the analytical results from Dynäs.

(Fig. 11), being 0.14 mg/g at 1.4 m, increasing to 0.25 mg/g at 2.5 m. The curve then drops to 0.18 mg/g at 3.5 m. From 3.5 to 5.5 m the values show an increase to about 0.23 mg/g and from 5.5 to 11.2 m a decline from 0.23 mg/g to about 0.1 mg/g. Between 11.2 and 13.3 m the manganese content increases to 0.25 mg/g, although at 12.6 metres, the content is 0.14 mg/g.

Exchangeable magnesium. — The magnesium content was determined in the same samples as the iron down to 13.3 m (Fig. 11). At 1.4 m the content is 0.26 mg/g and at 2 metres 0.34 mg/g. The curve drops from 2.5 m to 0.42 mg/g at 5.5 m. Between 5.5 and 7.2 m there is a decrease to 0.32 mg/g. From 7.2 to 9.3 m the values rise again to 0.47 mg/g. Between 9.5 and 11.3 metres the magnesium content remains constant at 0.33 mg/g. There is an increase from 0.28 mg/g to 0.36 mg/g between 11.6 and 12.3 m, the curve then descends to 0.27 mg/g at 13.3 m.

Exchangeable sodium. — The sodium content was determined in the same samples as the iron down to 13.3 m (Fig. 11). It increases from about 0.2 mg/g to 0.9 mg/g in the uppermost layer, i.e. between 1.4 and 4.1 m. Then there are values of about 0.8 mg/g at 4.5 and 5.2 metres. At 5.5 metres a peak of 9.6 mg/g appears; the sodium content then falls to 0.7 mg/g at 7.2 and 7.5 m. From 7.5 to 8.2 m the value increases to 0.9 mg/g, only to fall again between 8.2 and 9.6 m. From 9.6 to 11.6 m the sodium content remains constant at about 0.45 mg/g. At 12.3 m the value is 0.64 mg/g; there is then a decrease to 0.24 mg/g at 13.3 m.

Exchangeable potassium. — The potassium content was determined in the same samples down to 13.3 m (Fig. 12). It increases from about 0.2 mg/g to 0.44 mg/g between 1.4 and 5.2 m. At 5.5 to 7.2 metres a rise occurs from 0.44 mg/g to 0.26 mg/g and followed by a further increase to about 0.38 mg/g from 7.2 to 8.7 m. Between 8.7 and 10.6 m the content declines to 0.26 mg/g. From 10.6 to 12.7 m the curve climbs to 0.5 mg/g. At 13.3 m the potassium content is 0.26 mg/g.

Exchangeable calcium. — The calcium content too was determined in the same samples as the iron down to 13.3 m (Fig. 12). The curve descends from 0.42 mg/g to 0.34 mg/g in the uppermost layer, 1.4 to 3.1 m. The valeus then fluctuate and increase to 0.64 mg/g at 5.5 m. From 5.5 to 7.2 m there is a decrease to 0.4 mg/g, followed by an increase to 0.58 mg/g at 8.2 and 8.5 m. From 8.5 to 11.6 m the values fall to 0.45 mg/g. At 12.3 m the calcium content is 0.6 mg/g and at 13.3 m 0.34 mg/g.

Dynäs, Core A

Stratigraphy. — Table 6 shows the stratigraphy of the sediment cores.

Grain-size distribution. — Grain-size analyses were performed at every metre of the core from 1.8 to 10.6 m (Fig. 14). The clay content varies only slightly between 1.7 and 6.7 m below surface; a slight increase from 24 % to 26 % appears. From 6.7 to 8.8 m the content increases to 44 % and, from 8.8 to 10.5 m, to 46 %. The amount of fine silt varies between 25 and 50 %. Thus it is the modal fraction of this section. From 1.7 to 5.7 m the content is constant at 65 %, followed by a decrease to 58 % at 6.7 m. From 6.7 to 7.8 m the fine silt content increases to 67 % and from 7.8 to 8.8 m to 94 %. At 10.5 m the value is 89 %.

The curves of medium and fine silt run parallel through the upper layers. Downwards they first diverge and then, in the deepest (glacial) part of the section, converge. The content of medium silt varies between 5 % and 28 %. The curve of coarse silt is similar to that of medium silt, the values decreasing downwards. No coarse silt is found below 8.8 m.

Water ratio. — The water ratio was determined every 34 cm between 0.5 and 12.8 m below surface (Fig. 13). It varies between 20 % and 85 % throghout the bed sequence. In the uppermost layer, between 0.5 and 1.8 m, the water ratio increases from 20 % to about 60 %. From 1.8 to 2.8 m the ratio approaches 60 %. The curve then drops to 55 % at 3.5 m; from there to 5.5 m the curve fluctuates downward to 85 %. At 5.8 m a fall occurs to 70 % and between 5.8 and 7.6 m the curve rises to 83 %. Between 7.6 and 9.6 m there is a fairly constant decrease in water ratio to 36 % and from 9.6 to 12.8 m the curve falls to 26 %.

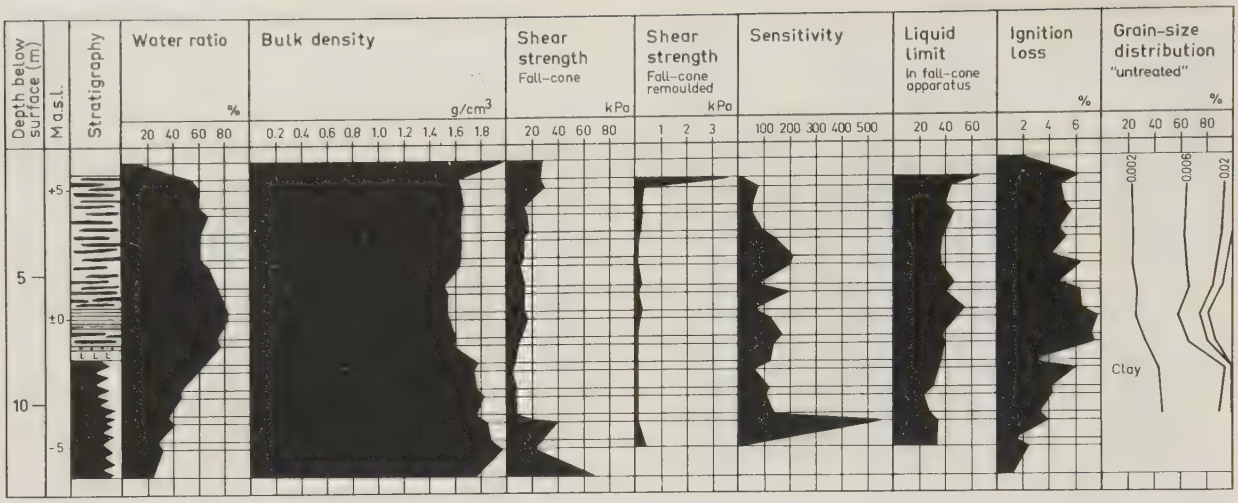

Fig. 14. Graphical presentation of the analytical results from Dynäs.

Bulk density. — The bulk density (Fig. 13) was determined in the same samples as the water ratio. At 0.5 m it shows a high value, 9.4 g/cm^3, while at 1.1 m it reaches 1.55 g/cm^3. From 1.5 to 4.2 m there is an increase from 1.64 g/cm^3 to 1.68 g/cm^3, followed between 4.2 and 5.8 m by a decrease to 1.56 g/cm^3. Between 5.8 and 7.9 m the bulk density remains constant around 1.57 g/cm^3. From 7.9 to 9.5 m the curve climbs to 1.9 g/cm^3, and then drops to 1.84 g/cm^3 at 10.6 m. From 10.6 to 11.3 m the bulk density rises to 1.98 g/cm^3 followed by a decline to 1.92 g/cm^3 at 12.3 m.

Table 6. Dynäs, stratigraphical description of the sediment core.

Depth below surface, metres	Description
0 — 1.10	Dry crust, reddish-brown clay
1.10— 6.31	Clay, grey with black bands. A piece of wood was found at 2.68 m
6.31— 6.87	Clay, grey with micro-varves
6.87— 7.04	Clay, grey with remoulded microvarves
7.04— 7.16	Clay, grey with black bands
7.16— 7.74	Clay, grey with black bands, 1—2 cm apart
7.74— 7.83	Clay, grey with black sulphide spots
7.83— 7.86	Clay, grey, homogeneous and fluid
7.86— 7.87	Fine silt
7.87— 7.875	Clay, grey
7.875— 7.97	Fine silt
7.97— 7.985	Clay, grey, homogeneous, fluid
7.985—7.99	Fine silt
7.99— 8.01	Clay, grey, homogeneous, fluid
8.01— 8.02	Fine silt
8.02— 8.10	Clay, grey, homogeneous, fluid
8.10— 8.18	Fine silt, grey
8.18— 8.28	Clay, grey, homogeneous, fluid
8.28— 8.42	Clay, grey, varved (varves ~ 1 mm; glacial clay), fluid
8.42— 9.09	Clay, grey, partly with 1 mm-thick varves
9.09— 9.27	Clay, grey with 1 mm-thick varves (glacial clay)
9.27— 9.31	Fine silt, grey
9.31— 9.71	Clay, grey with remoulded varves
9.71— 9.81	Clay, grey, homogeneous, fluid
9.81—10.31	Clay, grey, fluid; when dried 1 mm-thick varves appear
10.31—11.17	Clay, grey, varved. In the upper part the varves are 1 mm in thickness and in the lower layer 1 cm
11.08—11.09	Coarse silt, grey
11.17—12.19	Clay, grey, varved. In the upper part the varves are about 1 cm in thickness and further down about 5 cm
12.19—12.87	Sample lost
12.87—13.21	Fine sand, grey

In situ shear strength, field-vane apparatus. — Determinations were made every 34 cm between 0.8 and 8.2 m below surface (Fig. 13). The shear strength varies between 10 and 38 kPa. In the uppermost layer, 0.8—1.5 m, the shear strength approaches 38 kPa while at 1.8 m it is 17 kPa. From 1.8 to 4.2 m the shear strength decreases, although fluctuating, to 13 kPa only to rise again to about 15 kPa between 4.2 and 6.5 m. In the lowest part of the sequence, 6.5—8.2 m, there is a decrease to approximately 10 kPa.

Sensitivity, field-vane apparatus. — The sensitivity was calculated every 34 cm (Fig. 13), and varies between about 9 and 32. In the uppermost layers, from 0.8 to 1.5 m, the sensitivity approaches 32, and reaches 15 at 1.8 m. Like the shear strength, it decreases to 10 from 1.8 to 4.2 m. Between 4.2 and 5.2 m there is a slight increase, to 12. At 5.5 and 6.2 m there are two peaks of 22 and 26. They are intersected by trough of 16 at 5.8 m. From 6.5 to 8.2 m the sensitivity consistently declines from 14 to 9.

Undrained shear strength, fall-cone test. — With two exceptions the shear strength was determined every 34 cm throughout the section (Fig. 13). It varies between 6 and 78 kPa. The highest value is found 0.8 m below surface; the shear strength then decreases to 20 kPa at 1.8 m. From 1.8 to 9.6 m there is a fluctuating decrease to 6 kPa. Between 9.6 and 12 m the values climb to 63 kPa. At 12.8 m the shear strength is 40 kPa.

Undrained shear strength, unconfined compression test. — Unconfined compression tests were performed in the same samples as the fall-cone tests, from 1.15 to 11 m below surface (Fig. 13). The shear strength varies between 8 kPa and 18 kPa. At 1.5 m it is 17 kPa, followed by a fluctuating decrease to 11 kPa at 4.5 m. From 4.5 to 6.2 m the shear

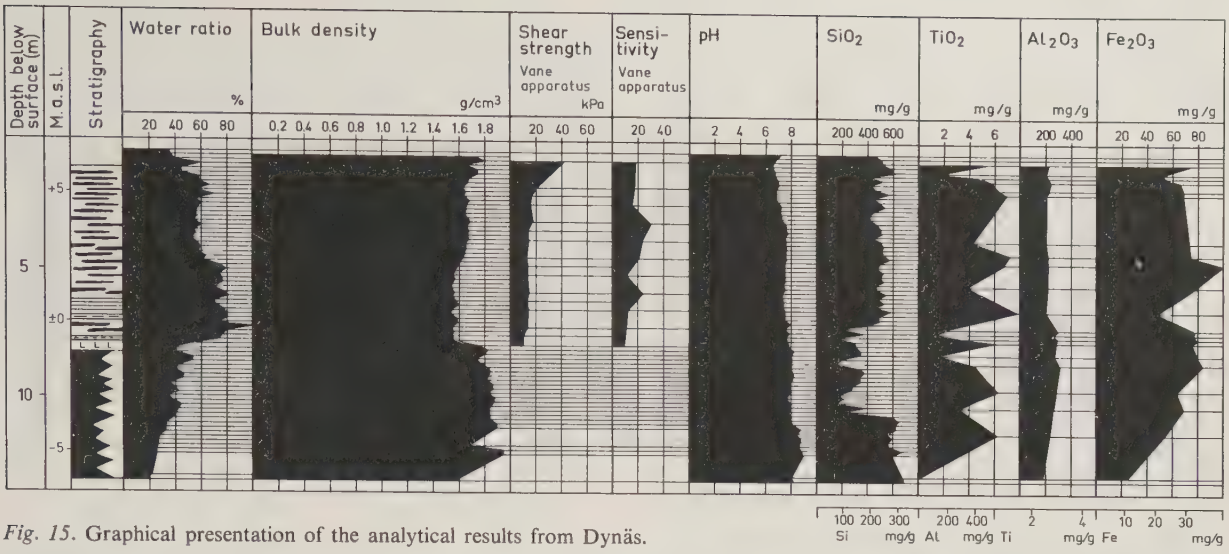

Fig. 15. Graphical presentation of the analytical results from Dynäs.

strength increases to 19 kPa with a subsequent decrease to 8 kPa from 6.2 to 7.9 m. In the deepest layers down to 11 m the shear strength rises to 12 kPa.

Liquidity index. — The liquidity index was calculated almost every 34 cm from 1.2 to 11.6 m below surface (Fig. 13). The curve fluctuates greatly between 2 and 11 throughout the sequence. From 1.2 to 5.5 m the liquidity index fluctuates strongly with an rising trend from 2 to about 8. From 5.5 to 6.2 m it decreases to about 2 while from 6.2 to 9.2 metres there is a fluctuating increase to 11. Between 9.2 and 11.6 m there is a decrease to 4.2 but at 9.6 metres there is a local trough of 2.4.

Carbon content. — The carbon content was calculated in only 22 samples throughout the section (Fig. 13). It varies between 0.2 and 2.3 %. In the uppermost layer, from 0.8 to 1.8 m, the carbon content ranges between 2 and 2.4 %, reaching 1.6 % at 2 m. Between 2 and 4.7 m it remains constant around 1.5—1.7 %. From 4.7 to 6.6 m it increases to 2.1 %. The lowest layer, from 6.6 to 13 m, presents a fluctuating decrease to 0.2 %.

Sulphur content. — The sulphur content (Fig. 13) was determined on the same samples as the carbon content. It varies between 0.1 and 0.9 %. From 1.2 to 7.2 m it remains constant around 0.3 %. At 7.4 m the sulphur content is 0.9 %, thereafter decreasing to 0.1 % at 8.6 m. The sulphur content is 0.1—0.2 % between 8.6 and 13 m.

Dynäs, core B

Water ratio. — The water ratio was determined every alternate 34th and 68th cm from 0.6 to 12.8 m below surface (Fig. 14). It varies between 15 and 82 %, with a maximum at 6.5 m. At 0.6 m the ratio is 15 % and by 1.7 metres has risen to 60 %; from 1.7 to 4.4 m it is constant at 60 % apart from a single value of 66 % at 2.3 m. Between 4.4 and 6.5 m it increases to 82 % and from 6.5 m oscillates downward to 24 % at 12.8 m.

Bulk density. — The bulk density (Fig. 14) was determined in the same samples as the water ratio. It varies between 1.5 and 1.98 g/cm^3. At 0.6 m it is 0.98 g/cm^3; then from 1.4 to 4.7 m it remains constant, around 1.63 g/cm^3. Between 4.7 and 5.5 m it decreases to 1.5 g/cm^3 and from 5.5 to 7.7 m to 1.58 g/cm^3. From 7.7 to 11.8 m the bulk density increases with a fluctuating tendency to 1.98 g/cm^3. At 12.8 m it is 1.76 g/cm^3.

Undrained shear strength, fall-cone test. — Fall-cone tests were performed at the same depths as the water ratio determinations (Fig. 14). In the uppermost layer, 0.6—1.7 m, the shear strength is about 18 kPa, and at 2.4 m 14 kPa. From 2.4 to 6.8 m the shear strength fluctuates around 14 kPa. At 6.8 m the value is 17 kPa, afterwards falling to 5 kPa at 8.8 m. From this depth to 10.5 m the shear strength increases to 9 kPa. In the lowest layer, 10.5—12.8 m, the shear strength fluctuates greatly, increasing to 68 kPa; at 11.8 m, however, the value is 22 kPa.

Remoulded shear strength, fall-cone test. — Tests were preformed on these same samples from 1.3 to 11.7 m (Fig. 14). The highest value is 3.6 kPa, at 1.3 m. From 1.7 to 4.7 m the shear strength decreases from 0.3 kPa to 0.1 kPa. Between 4.7 and 7.5 m it is 0.1—0.2 kPa, except at 5.5 and 6.5 m which present a remoulded shear strength of 0.3 kPa. From 7.5 to 10.8 m the shear strength remains constant at 0.1 kPa. In the lowest layer, 10.8—11.7 m, the remoulded shear strength increases to 0.5 kPa.

Sensitivity, fall-cone test. — The sensitivity was calculated on the samples subjected to the fall-cone test (Fig. 14). It varies between 20 and 550. The lowest value is found 1.3 m below surface. From 1.3 to 1.7 m the sensitivity increases to 80 and between 1.7 and 2.7 metres declines to 50. Between 2.7 and 4.4 m there is an increase to about 200 followed by a drop to 70 at 5.5 m. At 5.8 m it is about 200 and at 6.5 m 70 again. From 6.5 to 7.5 m the sensitivity increases to 170; it then falls to 130 at 8.5 m and to 60 at 8.8 m. Between 8.8 and 10.5 m it rises to 140. At 10.8 m it reaches 550 and at 11.7 m 30.

Fall-cone liquid limit. — The liquid limit was determined via fall-cone tests at every alternate 34th and 68th cm

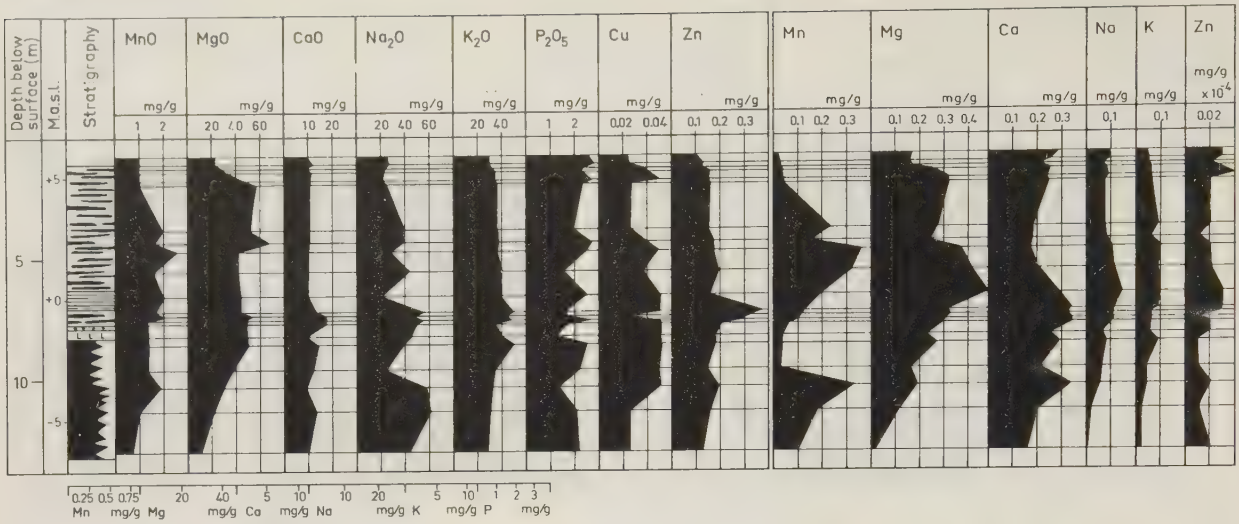

Fig. 16. Graphical presentation of the analytical results from Dynäs.

throughout the bed sequence (Fig. 14). The values vary between 24 and 65, with the highest value at the top. In the uppermost layer 1.3–2.4 m, the liquid limit decreases from 65 to 40, followed by a fluctuating decline to 36 at 4.7 m. From 4.7 to 6.5 m the curve oscillates downwards to 55. Between 6.5 and 9.8 m there is a drop to 24, with a subsequent increase to 33 in the lowest layer.

Ignition loss. – The ignition loss was determined on every alternate 34th or 68th cm from 0.6 to 12.8 m below surface (Fig. 14). It varies between 1.3 % and 7.7 %. At 0.6 m the ignition loss is 2 %, followed by an increase to 6 % at 1.3 m. From 1.3 to 4.4 m there is a fluctuating decrease to 4.2 %. Between 4.4 and 6.7 m the values fluctuate upwards to a peak of 7.7 %. From 6.7 m the curve oscillates violently and drops to 1.3 % at 12.8 m.

Dynäs, core C

Water ratio. – The water ratio was determined in the main at every 17 cm throughout the section from 0.4 to 13.2 m below surface (Fig. 15). It varies between 18 % and 80 % (100 %). In the uppermost layer, 0.4–2.1 m, there is a fluctuating increase from 35 % to 70 %, and from 2.1 to 3.8 m a decrease to 52 %. Then, between 3.8 and 5.0 m, the water ratio increases to 80 % and from 5.0 to 7.5 m fluctuates between 70 % and 80 % with a slight tendency to increase. From 7.5 to 8.0 m there is a decrease to about 40 %. At 8.4 m the water ratio is 53 %, decreasing thereafter to 18 % at 13.2 m.

Bulk density. – Like the water ratio the bulk density was mostly determined at every 17 cm from 0.4 to 13.2 m below surface (Fig. 15). The uppermost layer, from 0.4 to 1.8 m, presents a decline from about 1.8 g/cm^3 to 1.64 g/cm^3, followed from 1.8 to 3.8 m by a slight increase to 1.68 g/cm^3. From 3.8 to 5.2 m the curve drops to 1.56 g/cm^3. At 5.2 to 7.2 m there is a fluctuating decrease to 1.54 g/cm^3, with a subsequent increase to 1.83 g/cm^3 between 7.2 and 8.1 m. This is followed by a fluctuating increase to 1.94 g/cm^3 at about 12 m. At 11.8 m, however, the bulk density approaches 1.7 g/cm^3, and, at 13.2 metres 1.58 g/cm^3.

In situ shear strength, field-vane apparatus. – Tests were made at every alternate 34th and 68th cm from 0.8 to 7.9 m below surface (Fig. 15). The shear strength varies between 10 and 40 kPa. At 0.8 m it is about 40 kPa, after which it decreases to 16 kPa at 2.4 m and 14 kPa at 7.2 m. In the lowest layer, from 7.2 to 7.9 m, it decreases to 10 kPa.

Sensitivity, field-vane apparatus. – The sensitivity was calculated at the same depths as the shear strength tests (Fig. 15). It varies between approximately 10 and 30. In the uppermost layer, from 0.8 to 2.4 m, there is a decrease from 18 to 16 followed by an increase to about 30 from 2.4 to 3.2 m. Between 3.2 and 5.2 m the sensitivity decreases to 10. From 5.2 to 7.9 m there is a drop to 9, while at 5.8 m a single value of 24 appears.

pH. – The pH values were determined in principle every 17 cm from 0.4 to 13.2 m below surface (Fig. 15). The values vary between 6.5 and 8.8. In the uppermost layer, from 0.4 to 2.1 m, they fluctuate around 7, while from 2.1 to 3.5 m the pH curve rises to 7.7. Between 3.5 and 6.8 m the pH is fairly constant at about 7.7. From 6.8 to 9.1 m there is an increase to 8.2 followed by a decrease to 7.6 from 9.1 to 9.9 m. From 9.9 to 12.1 m there is a fluctuating increase to 8.8. The curve then drops to about 8 at 13.2 m.

Total contents of elements (Figs. 15 and 16). – The SiO_2 content was determined in the same samples as the pH. In the upper layers of the bed sequence, from 0.4 to 6.9 m, the content fluctuates around 500 mg/g ± 80 mg/g. At 1.1 m, however, the value reaches 610 mg/g. From 6.9 to 7.2 m the SiO_2 content decreases to about 200 mg/g and between 7.2 and 10.4 m the curve fluctuates strongly around 300 mg/g ± 100 mg/g. From 10.4 to 10.6 m the curve climbs towards 600 mg/g. In the lowest layer, from 10.6 to 13.2 m, there is a fluctuating increase to 680 mg/g.

The TiO_2 content was determined from about 0.8 to 13.2 m below surface. The samples analysed were fewer than the SiO_2 analyses, which complicates the interpreta-

tion. The values fluctuate widely between 1.4 and 5.9 mg/g throughout the sequence being around 5 mg/g in the upper layers with a maximum of 5.8 mg/g at 6.5 m. The TiO_2 content reaches 1.4 mg/g at 7.4 m. Between 7.4 and 13.2 m the curve fluctuates strongly around 4 mg/g $\pm$ 1 mg/g. At 13.0 metres the content approaches 0.1 mg/g.

The *Al_3O_3* content was determined in these same samples. It varies between 180 and 320 mg/g. In the uppermost layers of the sequence, from 0.8 to 6.5 m, the Al_2O_3 content remains more or less constant around 200 mg/g. From 6.5 to 7.2 m there is an increase to 300 mg/g while between 7.2 and 8.1 m it fluctuates just below 300 mg/g. From 8.1 to 13.0 m there is a smooth decline from 320 mg/g to 180 mg/g.

The *Fe_2O_3* content was determined in the same samples as the TiO_2 content. It ranges from 25 to 100 mg/g. In the uppermost layer, from 0.8 to 4.3 m, the Fe_2O_3 content increases from about 70 mg/g to 75 mg/g and from 4.3 to 4.7 metres to about 100 mg/g. At 4.7 to 6.5 m it declines to 50 mg/g. Between 6.5 and 7.2 m there is a rise to 77 mg/g, followed, between 7.2 and 8.6 m, by a slight fluctuating increase to 84 mg/g. In the lowest layer, from 8.6 to 13.0, the Fe_2O_3 content oscillates downward to 25 mg/g.

The *MnO* content was determined, still using the same samples. It varies between 0.7 and 2.5 mg/g throughout the sequence. In the uppermost layer, from 0.8 to 2.0 m, the content is constant at 1 mg/g. From 2.0 to 4.7 m there is an increase to 2.5 mg/g, although the value is 1.6 mg/g at 4.3 m. Between 4.7 and 5.5 m the value falls to 1.6 mg/g but at 5.5 to 6.5 m increases once more to 2 mg/g. From 6.5 to 7.5 m the tendency is a decrease to about 1.4 mg/g. In the interval 7.5—9.6 m the MnO content is constant at 1.4 mg/g. At 10.3 m it reaches 1.9 mg/g, then declines to about 1 mg/g at 11.3 m and 0.7 mg/g at 13.0 m.

The *MgO* content was determined in the same samples as the TiO_2 content, and varies between about 11 and 66 mg/g. At the top, between 0.8 and 2.0 m, the content increases from about 20 to 57 mg/g. From 2.0 to 3.8 m there is a decrease to 52 mg/g. At 4.3 m the content reaches 66 mg/g and at 4.7 m 42 mg/g. Between 4.7 and 8.5 metres the tendency is a slight fluctuating increase to 50 mg/g. The lowest layer, from 8.5 to 13.0 m, shows a continuous decrease to 11 mg/g.

The determination of the *CaO* content was performed in the same sample as for the TiO_2. The CaO content varies between 10 and 18 mg/g. In the uppermost layer, between 0.8 and 6.5 m, the content is fairly constant around 10 mg/g. From 6.5 to 7.6 m the values increase to 18 mg/g, and between 7.6 and 10.3 m decline toward 10 mg/g. At 8.2 m, however, the CaO content is 10 mg/g. The content at 11.3 m is 13 mg/g and at 13.0 m 10 mg/g.

The *Na_2O* content was determined in the same samples as the TiO_2 content, and varies between 20 and 60 mg/g. The values decrease from 25 to 22 mg/g between 0.8 and 1.7 m. Then there is an increase to 40 mg/g at 4.3 m. At 4.7 m the Na_2O content is 29 mg/g and at 5.5 m 43 mg/g; it then decreases to 20 mg/g at 6.5 m, after which, between 6.5 and 7.2 m it climbs to 54 mg/g, then between 7.2 and 9.6 m falls to 25 mg/g. At the bottom the curve drops to 57 mg/g at 10.3 m and about 60 mg/g at 11.3 m. At 13.0 m the value is 44 mg/g.

The *K_2O* content was determined in the same samples as the TiO_2 content. It varies between 28 and 48 mg/g. In the uppermost layer of the bed sequence, from 0.8 to 6.5 m, there is a slight increase in the K_2O content, to about 40 mg/g and at 6.5 to 7.2 m to 48 mg/g; it then decreases to 35 mg/g at 7.7 m. Between 7.7 and 8.5 m there is an increase to 48 mg/g followed by a decrease to 34 mg/g at 9.6 m and to 28 mg/g at 13.0 m.

The *P_2O_5* content was determined using the same samples as for the TiO_2 value and varies between 1.3 and 2.8 mg/g. The content decreases from about 2.6 mg/g at 0.8 m to 2 mg/g at 3.8 m. From 3.8 to 4.3 m there is an increase to 2.7 mg/g, with a subsequent decrease to 1.5 mg/g at 5.5 m. Between 5.5 and 6.5 m the curve rises to 2.4 mg/g, followed at 6.5 to 8.7 m by a drop to 1.3 mg/g. At 7.5 m, however, the P_2O_5 content reaches 2.6 mg/g.

The *Cu* content was calculated by analysing the same samples as in the case of TiO_2. It ranges from 20 x 10^{-3} to 50 x 10^{-3} mg/g. The Cu content is 24 x 10^{-3} mg/g at 0.8 m, whereupon it increases to about 50 x 10^{-3} at 1.8 m. At 1.9 m it is 28 x 10^{-3} mg/g and at 3.8 metres 26 x 10^{-3} mg/g. From 3.8 to 4.7 m an increase occurs to 48 x 10^{-3} mg/g followed by a decrease to 36 x 10^{-3} mg/g at 5.5 m. The values then drop toward 50 x 10^{-3} mg/g at 6.5 m and 7.2 m. At 7.4 m the Cu content approaches 20 x 10^{-3} mg/g. Between 7.5 and 10.3 m the content is more or less constant around 50 x 10^{-3} mg/g. A decrease to 26 x 10^{-3} mg/g appears at 11.3 and 13.0 metres.

The *Zn* content, determined in the same samples as the TiO_2 content varies between 0.1 and 0.37 mg/g. From 0.1 mg/g at 0.8 m it increases to 0.16 mg/g at 1.4 m and by 3.8 m has fallen slightly to 0.15 mg/g. Between 3.8 and 5.5 m the curve rises to 0.19 mg/g, only to descend to 0.15 mg/g at 6.5 m. There is then an increase to 0.37 mg/g at 7.2 m, followed by a decrease to 0.18 mg/g between 7.2 and 8.2 m, and to 0.15 mg/g at 9.6 m. At 10.3 m the Zn content is 0.19 mg/g, with a subsequent decrease to 0.13 mg/g at 13.0 m.

Exchangeable ions. — The contents of exchangeable manganese, magnesium, calcium, sodium, potassium, and zinc were determined in the same samples as the oxides and elements discussed above, from TiO_2 to Zn (Fig. 16).

The *manganese* content varies between about 0.02 and 0.36 mg/g. At 0.8 m it is 0.02 mg/g, whereupon it increases to 0.04 mg/g at 1.9 m and to 0.36 mg/g at 4.7 m. At 4.3 m, however, the content is 0.16 mg/g. From 4.7 to 8.2 m the curve drops to 0.04 mg/g, and to 0.03 mg/g at 9.6 m. Between 9.6 and 10.3 m there is an increase to 0.33 mg/g, followed by a decrease to 0.1 mg/g at 13.0 m.

The *magnesium* content varies between 0.02 and 0.5 mg/g. In the top layer, 0.8—1.3 m, it approaches 0.16 mg/g, after which it increases toward 0.32 mg/g at 1.9 m. From 1.8 to 4.3 m there is a decrease to 0.24 mg/g, followed by an increase to 0.38 mg/g at 4.7 m and 0.5 mg/g at 6.5 m. In the lower sequences, 6.5—13.0 m, there is a fluctuating decrease to about 0.02 mg/g.

The *calcium* content varies between 0.16 and 0.34 mg/g. In the uppermost layer, 0.8—4.7 m, the curve drops from 0.28 to 0.17 mg/g except for a local peak of 0.21 mg/g at 1.3 m. From 4.7 to 7.2 m the values rise to 0.34 mg/g. At 7.7 m the content returns to 0.34 mg/g. Then there is a fluctuating decrease to 0.21 mg/g at 9.6 m. At 10.3 m the content is 0.33 mg/g, before decreasing to 0.16 mg/g at 13.0 m.

The *sodium* content varies between 0.01 and 0.14 mg/g. It is 0.1 mg/g at 0.8 m and then fluctuates down to 0.08 mg/g at 1.9 m. From 1.9 to 4.3 m the content is fairly constant at 0.08 mg/g. Between 4.3 and 6.5 m it increases to

0.14 mg/g and then decreases to 0.07 mg/g at 8.2 m. At 8.5 m it is 0.08 mg/g, followed by a drop to 0.01 mg/g at 13.0 m.

The *potassium* content varies between 0.02 and 0.1 mg/g. In the uppermost layers, 0.8–4.7 m, it increases from about 0.04 mg/g to 0.1 mg/g. At 4.3 m, however, there is a local trough at 0.06 mg/g. From 4.7 to 7.2 m the curve is rather constant, around 0.1 mg/g. At 7.4 m the content is 0.06 mg/g and at 8.2 m 0.05 mg/g. The curve then drops to 0.09 mg/g at 9.6 m. In the lowest layer of the section, 9.6–13.0 m, the potassium content decreases to 0.02 mg/g.

The *zinc* content ranges between 0.008 x 10^{-4} and 0.04 x 10^{-4} mg/g. In the uppermost layers, 0.8–1.9 m, it fluctuates around 0.03 x 10^{-4} mg/g $\pm$ 0.01 x 10^{-4} mg/g. Between 1.9 and 5.5 m the curve remains fairly constant at 0.02 x 10^{-4} mg/g with the exception of an isolated value of 0.01 x 10^{-4} mg/g at 4.3 m. The curve then rises to 0.03 x 10^{-4} mg/g at 5.5 and 7.2 m. From 7.2 to 8.5 m the values tend to decline, to 0.01 x 10^{-4} mg/g. They are then constant at 0.01 x 10^{-4} mg/g down to 9.7 m. At 10.3 m the zinc content approaches 0.02 x 10^{-4} mg/g while at 11.3 metres it is 0.01 x 10^{-4} mg/g. In the lowest sample, from 13.0 m, it represents 0.02 x 10^{-4} mg/g.

Discussion

Gammelgården

Stratigraphy and some general aspects. — For the details of the stratigraphy see Table 4.

Vertical fissures were observed in the core throughout the sequence. The sediment surface was there coated with a thin film of limonite (cf. Fromm 1965). As the film was present even at the moment of sampling, the fissures cannot result from disturbances from the coring. In all probability they were caused by the uplift of the land and the consolidation of the sediment. The film is attributed to circulation of oxygen-bearing water in the fissures.

After brief exposure to the air the black sediment under the limonite film oxidized assuming a red brown colour (Fig. 17). The occurrence of this type of fissures reduces the shear strength and the stability of the soil (cf. Broms 1972), particularly on slopes and at excavation of trenches for, *e.g.*, conduits. The tenacity occasionally demonstrated by the loosening of the teeth of the excavator bucket is a characteristic feature of the relatively loose but tough soil in excavation works.

The technical parameters are well known from this area (Schwab 1976). The values of the shear strength are low, < 10 kPa in the upper layers of the sequence, and about 20 kPa at a depth of 10 m. The ratio between the shear strength, τ_{fu}, and the stress-strain relationship, σ'_{vo}, shows that the sediment is slightly overconsolidated (Schwab *op. cit.*).

This result is not remarkable from a geological point of view; it is rather a natural phenomenon in areas with massive sediment deposits which were isostatically elevated after the last glaciation. The frequent occurrence of these vertical fissures promted our decision to abstain from shear-strength tests on samples from this site. The fissures would have influenced the test results giving misleading shear-strength values (cf. Gardemeister 1975). Full scale loading tests are preferable. Such tests were recently performed (Schwab *op. cit*) at various localities where the soil was classified as a black sulphur-rich sediment.

Correlation tests show that a number of the parameters are heavily dependent on the depth (Table 7). This is to be expected as the conditions of formation of the sediments, the sedimentation as well as the secondary (diagenetic) environment change in the course of time. The behaviour of the various parameters will be discussed below.

Table 7. Gammelgården: correlation coefficient (r) and significance (s) with respect to depth. N denotes the number of observation pairs.

	r	s	N
Water-ratio	−0.95	0.1	70
Water content	−0.95	0.1	70
Extractable iron	−0.86	0.1	44
pH	0.76	0.1	70
Bulk density	0.91	0.1	69
Ignition loss	−0.73	0.1	70

Fig. 17. Photo showing vertical fissure, oxide coated, in sediment from Gammelgården.

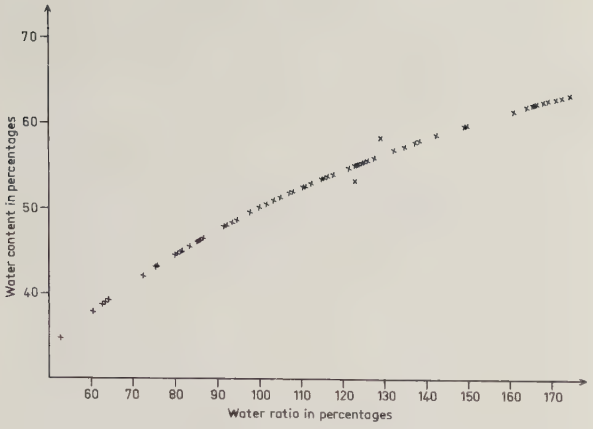

Fig. 18. The relationship between water content and water ratio.

Grain-size distribution. — The irregularities in the grain-size distribution are due to differences in environmental conditions during the sedimentation. One important cause in this connection is the variation of the contents of organic matter, and iron and manganese compounds in the sediments, as these affect the cementation and formation of aggregates. As mentioned above (see Discussion on p. 10) the aggregates complicated the pretreatment of the samples. Thus it is not possible to give any information on the proportions between aggregates and non-aggregated single grains in the different size fractions. Be that as it may, the silt is the modal fraction in the whole sequence. The highest clay contents are found between 11 and 13.5 m and in the lowermost layers.

Water ratio and bulk density. — In this study the water percentage of a sediment is described as the water ratio. However, in geological reports the water percentage is usually expressed in terms of the water content. In order to show that the different ways of presentation do not influence the results of the statistical treatment the correlation and the significance values of both the water ratio and the water content for the site Gammelgården are given in Table 7 p. 24. Furthermore the relationship between water content and water ratio is illustrated in Fig. 18.

The values of the water ratio and the bulk density show opposite trends throughout the sequence (cf. Hamilton 1976, Cato 1977). The water-ratio curve falls linearly from top to bottom while the bulk density curve shows a linear rise in the opposite direction. This indicates that the sediments are similar throughout. If any discontinities, such as layers of coarser sediments, had occurred in the sequence the curves for the water ratio and the bulk density would have shown irregularities. The different behaviour of the curves of the two parameters is due to the diminishing downwards of the porosity due to the increasing overburden.

pH. — The pH values increase from about 7 in the uppermost layer to about 9 at a depth of 23 m. The increase is almost linear. Increase of pH with depth is reported by many authors (cf., *inter alios*, Gardemeister 1975, Price 1976) and explained in terms of the redox-potential decrease in the formation of alkaline products during the anaerobic decomposition of organic matter in the sediment (see, *e.g.*, Olausson 1972). The pH regulating factors are discussed on page 5.

Ignition loss and carbon content. — The ignition loss amounts to 8—11 per cent in the upper half of the sequence and 6—8 per cent in the lower (Fig. 8). Like the water ratio this indicates a somewhat divergent sediment in the upper half of the sequence. Water and salts in the sediment influence the ignition loss values, although the determinations were performed at a moderate temperature, 550°C. A more reliable parameter, however, is the carbon content. As for the water content and the ignition loss the upper half of the sequence, above about 13.5 m, shows higher values for the carbon content than the lower, although less significant. This distribution may be due to an upwards increasing supply of organic matter to the sediments together with far advanced decomposition of the organic material in the deeper layers. As demonstrated by many authors the content of organic matter in the sediments generally increases with diminishing grain-size (see, *inter alios*, Trask 1939, Revelle & Sheppard 1939, Arrhenius 1947, Kuenen 1950, Emery 1960). As stated by Kuenen (*op. cit.*) the relationship between the content of organic matter and the grain-size distribution is due chiefly to environmental factors:

> The main factor regulating the content of organic matter in sediments is the nature of the accumulation environment: calm conditions are essential for the contemporaneous sedimentation of fine mineral particles and light organic matter.
>
> By reason of the pore width, fine-grained deposits preserve the enclosed organic matter far more thoroughly from oxidation than do coarser deposits. A sediment with a high proportion of large grains allows water to circulate more vigorously in the wide pores. The supply of oxygen results in increased decomposition and removal of organic matter.

There is no significant correlation between carbon content and increasing frequency of fine-grained material in the core from Gammelgården (Figs. 19 and 20). The causes are two: the method of pretreatment, preserving the aggregates, and the low number of pairwise analyses.

As regards the ratio between carbon content and ignition loss the conventional factor for long standing is 1.724, on the assumption that soil organic matter contains 58 per cent carbon (Russel & Engel 1928, Van Bemmlen, in Jackson 1958). There are, however, many theories where a division into surface soils and subsoils give different factors ranging between 1.7 and 2.5 (see, *inter alios*, Trask 1939, Trask & Patnods 1942, Jackson 1958). The state of oxidation in the sequence, the nature of the organic source material and the environment must be taken into consideration when interpreting the ratio (Emery 1960, Emery & Rittenberg 1952). In the core from Gammelgården it ranges between 2.4 and 4.2 with no significant pattern of distribution (Table 8).

Sulphur content. — The sulphur content fluctuates between 1 and 1.5 per cent and the distribution within the core shows a slight increase towards the top of the sequence. There is a slight similarity to the distribution of the fine-grained material. No correlation with the content of extractable iron and manganese can be demonstrated (Figs. 19 and 20). This depends on the paucity of pairwise analyses.

Extractable iron and manganese. — Gammelgården is the only site where iron and manganese were extracted. As

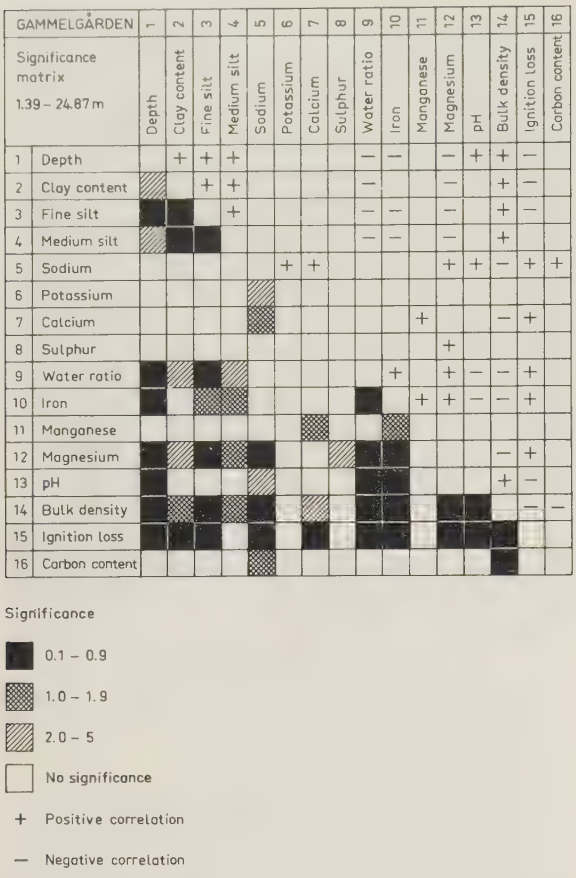

Fig. 19. Matrix showing the significance of the correlation tests from Gammelgården.

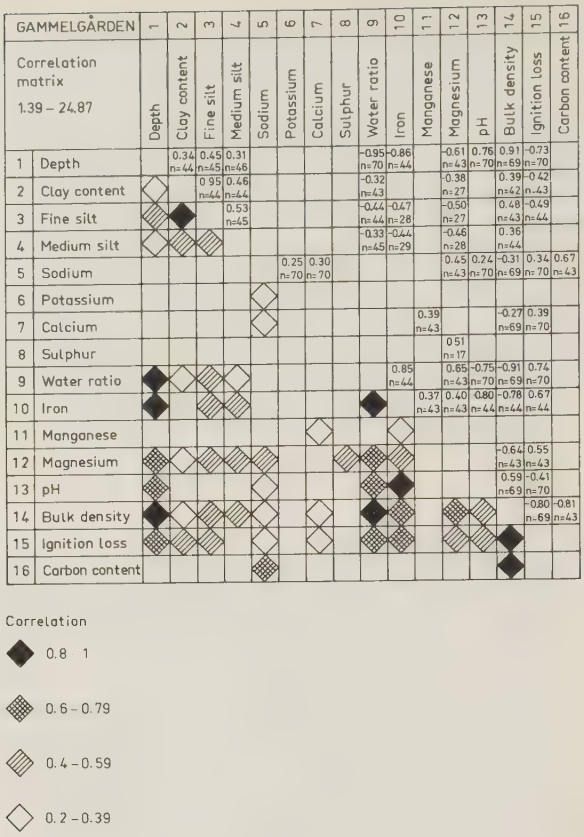

Fig. 20. Correlation matrix showing the interrelationships of the parameters studied in Gammelgården.

stated above (p. 14) the main possible sources of the iron extracted are hydroxides, sulphides and silicates. Without further investigation it is not possible to estimate the proportions of each. Judging by the universal dark colour and the odour of the sediment the monosulphides probably

Table 8. The ratio ignition loss/carbon content.

Depth (m)	Ratio	Depth (m)	Ratio	Depth (m)	Ratio	Depth (m)	Ratio
1.39	2.96	7.85		14.67		21.45	
1.73		8.19	3.18	14.99	2.97	21.81	2.65
2.07	2.90	8.55		15.33	3.30	22.13	
2.41		8.87	2.85	15.69	2.38	22.47	3.00
2.75	3.87	9.21		16.01		22.83	
3.09	3.12	9.57	3.48	16.35	2.88	23.15	2.50
3.43	3.35	9.89		16.71	2.54	23.49	2.21
3.77	3.36	10.23	2.83	17.03		23.85	4.23
4.11	2.96	10.59		17.37	2.37	24.17	3.00
4.47		10.91	2.69	17.73	2.64	24.51	2.64
4.79	3.36	11.25		18.05		24.87	2.92
5.13		11.61	2.43	18.39	3.05		
5.32		11.93		18.75			
5.49	2.73	12.27	2.79	19.07	2.55		
5.81		12.63		19.41			
6.15	3.11	12.95	2.38	19.77	3.23		
6.51		13.29		20.09			
6.83	3.65	13.65	2.97	20.43	2.96		
7.17	2.57	13.97	3.24	20.79			
7.53	2.77	14.31	2.68	21.11	2.96		

predominate. This theory is also supported by the reddish colouring of the sediment on drying and oxidation in contact with air. The iron distribution shows an increase from the bottom to the top of the sequence. Possible explanations will be discussed.

Ferric oxides are carried by rivers either as stabilized colloids or as adsorbed coatings on detrital particles. According to Shapiro (1964), suspensions of ferric colloids may be stabilized by, and intimately mixed with, organic matter. Thus, a high content of organic matter in a sediment can reveal a high content of iron.

By reason of their large specific surface, clay minerals are of great importance as agents for the transport of adsorbed iron oxid (Carroll 1958). Consequently, iron will be concentrated in fine-grained sediments. Moreover, iron minerals, *e.g.* magnetite and ferruginous silicates, can be transported and deposited as simple detrital particles.

Roots and root hairs of living plants generate organic acids (see, *inter alios,* Levinson 1974). They will release elements fixed in the sediment and make them available to the plants. When the plants die and decompose the elements will return to the top soil, causing a higher element concentration.

At the compaction of the sediments interstitial water with dissolved elements moved upwards, causing a rise of the total element contents in the upper layers of the sequence (see, *inter alios*, Eisma 1973, Cline & Upchurch 1973, Reinhard & Förster 1976). The significance of this

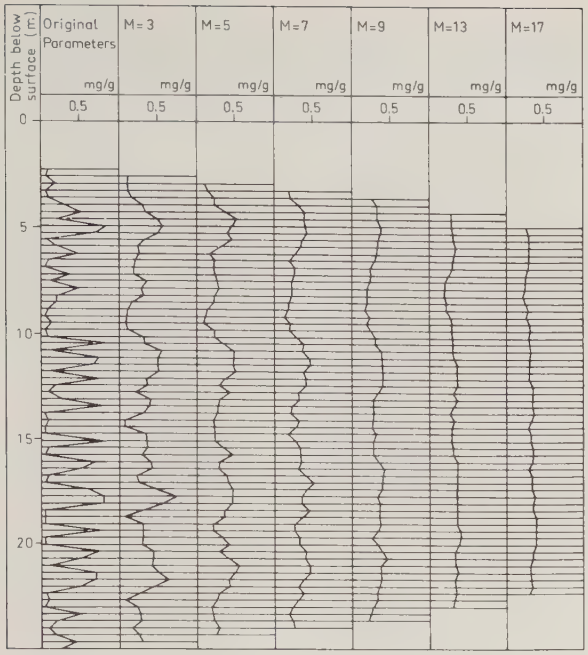

Fig. 21. Original data curve and smoothed curves for potassium, M denotes the smoothing interval.

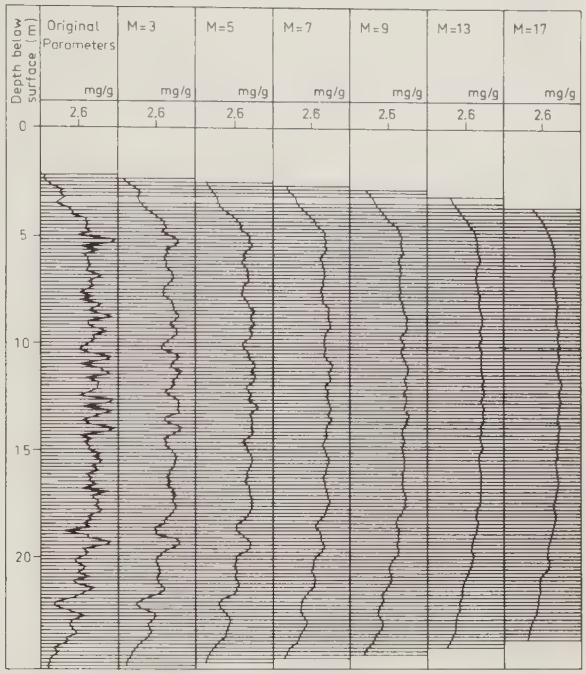

Fig. 22. Original data curve and smoothed curves for sodium, M denotes the smoothing interval.

process for the distribution of, *e.g.*, iron and manganese cannot, however, be estimated.

The high iron content in the upper half of the sequence may thus be due to:

conditions during the sedimentation,
high content of organic matter,
the mineral constituents in the shallow-water sediment,
accumulation due to biological activity,
the transport with the interstitial water of the sediment.

There are no criteria for assessing the compounding of the manganese with other elements. Judging by Garrels & Christ (1965, Fig. 6.13 p. 165 and Fig. 11.5 p. 387) manganese carbonate and manganese hydroxide may occur (proposed by Erik Eriksson). The manganese content shows the same distribution as the iron through all but the lowermost fourth of the sequence, 18.4—24.2 m below the surface; the mangenese content generally falls short of 5 per cent of those of the iron. In the lowest layer of the section there is an irregular rise in the manganese content. The cause is not known, however.

The supply of manganese to the sediments may be more or less due to the same factors as the iron.

The iron content is weakly to moderately correlated with the percentages of fine and medium silt (cf. p. 25). No correlation of iron and manganese with the percentages of clay is to be expected, in view of the pretreatment chosen. A point of great interest for the idea of the environment of formation is the fact that the sulphur and carbon curves show, although less distinctly, the same general trend as the iron and manganese curves, except for the uppermost, and lowermost parts of the manganese curve (see above). The absence of correlations of the iron content with the contents of sulphur and carbon certainly has a technical cause, the low number of pairwise analyses (cf. p. 45). The same may be true of the missing correlation between manganese and carbon. The correlation between iron content and ignition loss is marked, at 0.67, which is understandable considering the constituents released when a sample is heated.

The manganese shows no significant relation to the grain-size distribution except for the lowermost fourth of the sequence where the curve resembles that of medium silt. The poor correlation between iron and manganese, 0.37, is surely due to the divergent distribution of manganese in the lower layers, as the correlations were calculated on the whole bed sequence.

Exchangeable magnesium. — The exchangeable magnesium has a maximum value of 3.4 mg/g at 4.11 m. Then there is an almost linear decrease to 0.4 mg/g at 24.87 m. The distribution resembles that of extractable iron and to great extent exchangeable calcium regardless of the magnitude of the values. The uppermost section like, *e.g.*—the extractable iron and manganese, is affected by recent biological activity.

According to Wedepohl (1970) magnesium is released in the process of rock weathering; the ions are transported by rivers to the sea. Magnesium present in seawater can be enclosed in the pore space of the sediments; it either remains dissolved in the pore solutions or is used in late diagenetic formation of chlorite.

The magnesium in sediments may also originate from the alteration of magnesium-bearing minerals. Chlorite has a low weathering stability; thus it may be attacked and release magnesium (cf. Løken & Torrance 1971).

The magnesium distribution within the core from Gammelgården may be divided into two parts:

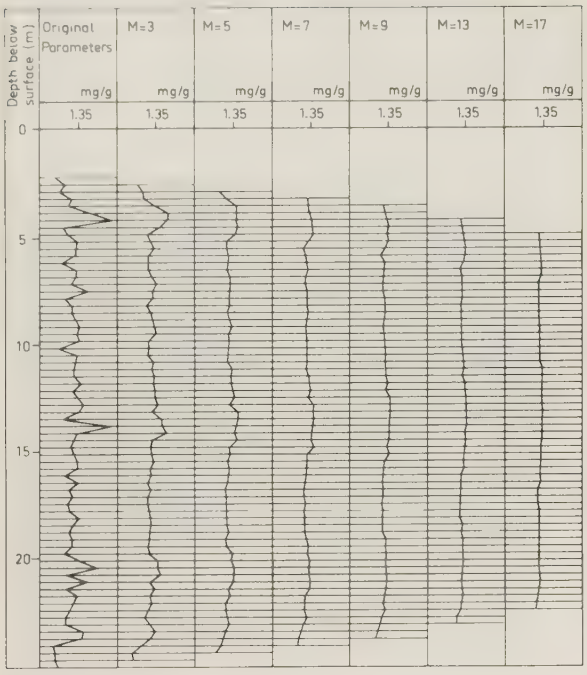

Fig. 23. Original data curve and smoothed curves for calcium, M denotes the smoothing interval.

the upper 3 m, affected by biological activity and possibly also by slightly differing environment during the deposition,

the lower, below about 3 m, with slowly increasing values upwards. The mechanism responsible for this is not known.

The correlations of magnesium with depth, water ratio and bulk density are given in Table 9. The primary correlation is that of magnesium with the water ratio; the others two are secondary.

Table 9. Coefficients (r) and significances (s) of some correlations of magnesium. N denotes the number of observations.

	r	s	N
Depth	−0.61	0.1	43
Water ratio	0.65	0.1	43
Bulk density	−0.64	0.1	43

Furthermore, the exchangeable magnesium is moderately but negatively correlated with the content of clay, of medium, and of fine silt. The correlation with exchangeable sodium is moderate and positive. The significance of these correlations is high for the fine silt and the exchangeable sodium, moderate for the medium silt and low for the clay content.

Exchangeable sodium, potassium, and calcium. — According to Jackson (1964) primary or detrital minerals make up most of the sand and silt fractions of most soils; these minerals are mainly quartz and feldspars. The sodium in most soils, particularly in well-leached soils is primarily in the form of detrital plagioclase (Mc Laughlin 1956).

Many authors investigated the sodium/potassium ratio and described the sodium as more mobile than the potassium during weathering (cf., *inter alios,* Anderson & Hawkes 1958, Short 1961). In most natural soils, the sodium/potassium ratio should decrease during ion exchange (Carroll 1959).

The theoretical order of the monovalent and the bivalent cations as regards exchange power and "adsorption" is according to Jenny (1927) $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$. Yet this order, by no means remains constant considering the different nature of the ion exchangers, *e.g.*, organic or inorganic, amorphous or crystalline structure together with the complicated activity conditions for colloid ions and electrolytes (cf. Wiklander 1947). In his discussion Krauskopf (1967) states this order for the relevant ions and says that the Na^{+} should be more readily adsorbed from a solution than the relatively larger K^{+}. On the other hand he observed that experimental results were usually the reverse.

According to Carroll & Starkey (1960) the exchange power is: $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$. Jørgensen (1965) therefore concludes that in the main clays deposited in seawater will probably have Mg^{2+} in exchangeable positions, while most clays from fresh-water will have Ca^{2+} in these positions. In consequence many authors used the contents of Mg^{2+} and Ca^{2+} as indicators of the environmental conditions during the desposition (cf., *inter alios*, Jørgensen 1965, Ericsson 1973). Ericsson (*op. cit.*), on investigating the Kramfors area, postulated that the exchangeable magnesium and calcium were relatively good criteria of paleosalinity. The exchangeable sodium and potassium, however, proved unsuitable for this purpose.

According to Tageyeva (1965) the sodium content of the interstitial water in recent marine sediment has not had sufficient time for alteration and is therefore reasonably similar to that of sea water. Some early changes do occur, however, such as, *e.g.*, the Ca^{2+} exchange in clays which releases Na^{+} to the solution.

Siever *et al.* (1965) state that little change occurs in the sodium content of interstitial water after deposition, except for an increase resulting from ion-filtration by clay membranes. As regards potassium, modern sediments presented a slight increase in potassium in the interstitial water after deposition, presumably owing to the hydrolysis of potassium feldspars. However, Billings *et al.* (1969) investigated ancient interstitial waters and found a decrease in the potassium content. They suggested that the potassium was lost from interstitial water to solids during diagenesis.

According to Wedepohl (1970) after entering a soil solution, the potassium is either used in the formation of potassium minerals, such as illite, adsorbed on other clays, or removed by circulating fluids.

The ions adsorbed to the mineral particles or to the organic matter in a sediment are chiefly derived from the water in which the sediment was deposited. The final proportion between the adsorbed ions is created by the mineral particles and the organic matter during the deposition (cf. Lambe 1958). Moreover exchangeable ions are derived from weathering processes in the sediment. According to Troedsson & Nyqvist (1973) the released sodium and potassium ions do not form a firm compound in the soil, and the adsorption of the anions is weak.

The effect of weathering due to variation in the pH is discussed by McNamara (1966); the potassium and the

sodium aluminosilicates break down more readily as the activity of H^+ in the interregular fluid increases relative to the activities of K^+ and Na^+.

Regarding the sodium, the potassium, and the calcium distribution in this investigation the potassium curve seems very irregular. The sodium and the calcium curves are irregular too but the pattern of distribution is obvious. To allow a more general picture of the distribution smoothed (cf. p. 15) curves are presented in Figs. 22, 21, and 23. These curves demonstrate that the exchangeable sodium has a distribution similar to that of the exchangeable magnesium and in part to that of, *e.g.*, the extractable iron. Thus, in the uppermost layers of the sequence the sodium curve, like the curves of the other exchangeable ions determined reflects influence by the biological activity. But considering the smoothed curve, the tendency of, *e.g.*, the extractable iron to decrease in the lower layers is obvious. In the interval from 3 to about 13 m the content of exchangeable sodium remains fairly constant, although fluctuating. The curve then steadily declines towards the bottom of the sequence.

The sodium is markedly correlated with the carbon content (r=0.67), moderately correlated with the magnesium (r=0.45) and weakly correlated with the potassium, the calcium, the pH, the bulk density, and the ignition loss.

The marked correlation with the carbon content seems natural in view of the high cation-exchange capacity of the organic matter. The considerably weaker correlation with the ignition loss may be an effect of the complex compound of this parameter (cf. p. 25—ignition loss). The irregular distribution of the exchangeable potassium throughout the section presumably strongly influences the correlation with the exchangeable sodium, giving low values. The correlation of sodium with the exchangeable calcium is weak. This may be an effect of the great difference between the divalent calcium ion and the monovalent sodium ion (cf. above, and Ericsson 1973). Exchangeable sodium is also weakly correlated with the bulk density which may be an secondary effect due to the relationship between the bulk density and the water ratio (cf. above). As the pH shows an almost linear distribution throughout the sequence the weak correlation with the exchangeable sodium may be a secondary effect like the correlation with the bulk density.

The potassium curve is the least regular. But the pattern of distribution is quite clear in the smoothed curve. There are accumulations of potassium in sequences with more fine-grained material (cf. the clay content Fig. 9).

As regards the calcium content the distribution is comparatively constant within the sequence regardless of the decrease in the uppermost and lowermost layers. At the top the vegetation affects the distribution and at the bottom the influence of the underlying sandy layer may cause a leaching.

In the main layers of the sequence the calcium fluctuates around 1 mg/g. As these ions are exchangeable and the exchange power related as stated the reason for the strong fluctuation of especially the potassium can be explained in terms of:

weathering in the sediment, aggravated in specific layers by the grain-size and related to fluctuations in the pore pressure (a pumping effect),

accumulation of easily exchangeable ions on particles with a large specific surface.

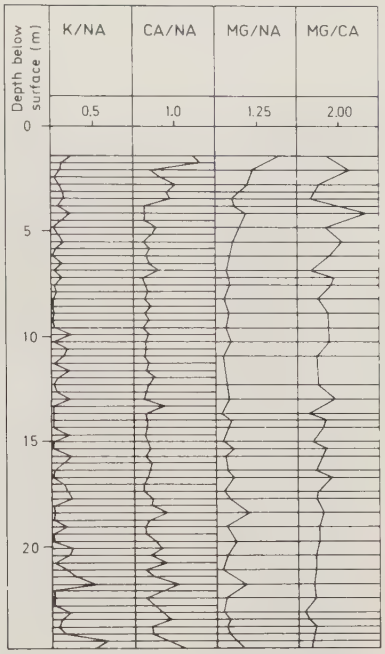

Fig. 24. Curves showing the ratios between the contents of the exchangeable ions potassium/sodium, calcium/sodium, magnesium/sodium, and magnesium/calcium.

A combination of these effects assuredly explains the uneven distribution of these exchangeable ions in the sediment. Considering the exchange power for the ions the "fluctuations" of the curves agree well with the differences in the exchange power.

Judging by the curves showing ratios (Fig. 24) the contents of the exchangeable ions, potassium/sodium, calcium/sodium, and magnesium/sodium present increased values in the lowermost and uppermost layers. In the main part of the sequence the curves show a fairly constant distribution. As high ratios for these ions possibly reflect a low salinity of the water in which the sediment was deposited (cf. Ericsson *op cit.*, Discussion above) the lowermost layers of the sequence with relatively high ratios may indicate deposition in a fresh or nearly fresh water environment. The covering layers of the sequence may reveal a brackish or poor saline milieu while the uppermost section may reflect the decrease in salinity during the evolution of the Littorina Sea (cf. Ericsson *op. cit.*).

This distribution corresponds to that expected by reason of the evolution of the Littorina Sea.

High ratios between the magnesium and calcium would seem to represent a saline environment (see schedule Table 1, p. 3 in Ericsson *op. cit.*) while low ratios indicate fresh water. In view of the manganese/calcium ratios throughout the sequence (Fig. 24) the ratios in the lowermost layers are low, about 0.5—1, possibly reflecting a fresh or slightly brackish deposition environment. But the curve rises steadily towards the upper part of the section. According to the Discussion this would imply a more saline water environment in the evolution of the Littorina Sea. However, this contradicts the results of the other ratios described above and Ericsson's assumption (see above) that the magnesium and calcium are good indicators of the deposition environment. The ratios between

the magnesium and the calcium thus cannot be unambiguously interpreted.

Conclusions. — The characteristic features of these sediments are:

the pitch black colour of the fresh sediment,

the odour on drying,

the uneven shrinkage on drying with simultaneous appearance of banding and change of colour upon oxidation,

the vertical fissuring in the sediment, even at great depths.

The vertical fissuring hampered the routine shear-strength tests. The shear-strength properties were studied at this site by Schwab (1976), and the upper 10 m reveal a sediment with very low shear strengths, less than 10 kPa. Below that depth the shear strength is low, less than 20 kPa. According to the present study there are differences throughout the sequence. From the ignition loss and carbon content determinations the sequence may be divided into an upper section — 0 to 10 m — with high values, a transition section — 10 to 17 m — with decreasing values, and a lower section with fairly constant values. These differences are also reflected in the water-ratio curve, although less markedly. The compaction reflected in the water ratio and bulk density determinations which are partly dependent on the ignition loss and carbon content is certainly the chief cause of the poor shear-strength properties. The pH distribution shows a slight increase with increased depth. Presumably, the environment is reducing within the whole section. The sulphur-content distribution remains more or less constant throughout the sequence with a slight increase from the bottom upwards. It is probable that all sulphur is compounded to iron in the form of metastable monosulphides. The extractable iron and manganese show a similar distribution except for the lower layers of the sequence where the manganese presents unexpectedly high values. The reason is not known.

The ratio curves for the exchangeable ions, potassium/sodium, calcium/sodium, and magnesium/sodium, reveal the expected salinity changes in the Littorina Sea. The ratio between exchangeable magnesium and calcium, however, is contradictory.

Rödäng

Stratigraphy and some general aspects. — For the details of the stratigraphy see Table 5.

The bed sequence reveals an evolution from the varved glacial clay at the bottom to a recent postglacial sulphide-bearing sediment at the top. The stratigraphy at this site mainly corresponds to those described by, *e.g.*, Gripenberg (1934), Ignatius (1958, 1964), Purokoski (1958), Manheim (1961), Hyyppä (1964), Fromm (1949, 1965), Jerbo (1965), Modig (1967), Ericsson (1970, 1973), and Winterhalter (1972).

The pitch-black, apparently homogeneous sediment in the upper layers of the section merges into a grey sediment further down (cf. Fig. 25). The differences in colouring may be an effect of the state of reduction (cf. p. 5). The grey clay with micro-varves shows diminishing varve thickness upwards (cf. Ignatius, 1958). Moreover, another pattern of black banding is visible in the section 4.5 to 12.4 m, black bands about 1 cm thick at 1—3 cm intervals. These bands are also micro-varved. At least the lower part of this section may be compared with the "gyttja-banded" clay described by Jerbo (*op. cit.*).

According to Ignatius (*op. cit.*) the lower black clay section dates from the "Lower Ancylus" stage in the evolution of the Baltic. Thus the topmost black sediments belong to the post-Littorina sediments. The grey silt layer, 13.5 to 13.9 m below the surface, may correspond to the possible drainage varve described by Fromm (*op. cit.*, cf. section E, p. 6). The fluid grey clay beneath, about 0.3 m thick, may correspond to the section F (see p. 6) described by Fromm (*op. cit.*) and Gardemeister (1975).

The core can be correlated with, *e.g.*, the general account by Fromm (see p. 6). However, Fromm's section D is missing at this site. Several layers or bands of silt and organic material were distinguished in the core. These layers may be due to occasional changes in the transport capacity of the water. The layers and bands observed are specified in Fig. 27.

It should be mentioned that the vertical fissuring of the sediments from Gammelgården (p. 24) was not observed in the core from Rödäng. According to Schwab (1976) the shear-strength and stress-strain ratio show that the sediment was never subjected to a load greater than the present overburden. However, the preconsolidation was designated a probable effect of delayed compression (cf. Bjerrum 1967, Schwab *et al.* 1976) partly caused by desiccation. As for the shear-strength properties and susceptibility to remoulding, see below.

With respect to depth the test shows marked correlations with wholly different parameters from the case with the slightly overconsolidated and relatively homogeneous sediments from Gammelgården. As the core from Rödäng consists of a number of distinct beds and the sediments are not preconsolidated the correlation of the water ratio and bulk density with depth should be different. Parameters markedly correlated with the depth are presented in Table 10. Their behavior will be discussed below.

Table 10. Rödäng: correlation coefficient (r) and significance (s) with respect to depth. N denotes the number of observation pairs.

	r	s	N
pH	70.47	0.5	34
shear strength (G250)	70.74	0.1	34
shear strength (fall-cone)	70.55	0.1	34
clay content	70.75	0.1	22
fine silt content	70.65	0.1	22
sulphur content	70.65	0.1	23
exchangeable manganese	—0.58	0.4	23
exchangeable potassium	70.46	3.0	22

Dating by pollen at Rödäng. — Arboreal pollen from the Rödäng core was analysed in order to obtain a relative dating of the different sequences. The analyses were made on samples taken at fairly close intervals (see p. 14). The results are presented in a summary diagram (Fig. 26), showing the changes in frequency with depth of the different pollens.

Considering the stratigraphy and the vegetational development the pollen diagram for Rödäng agrees closely

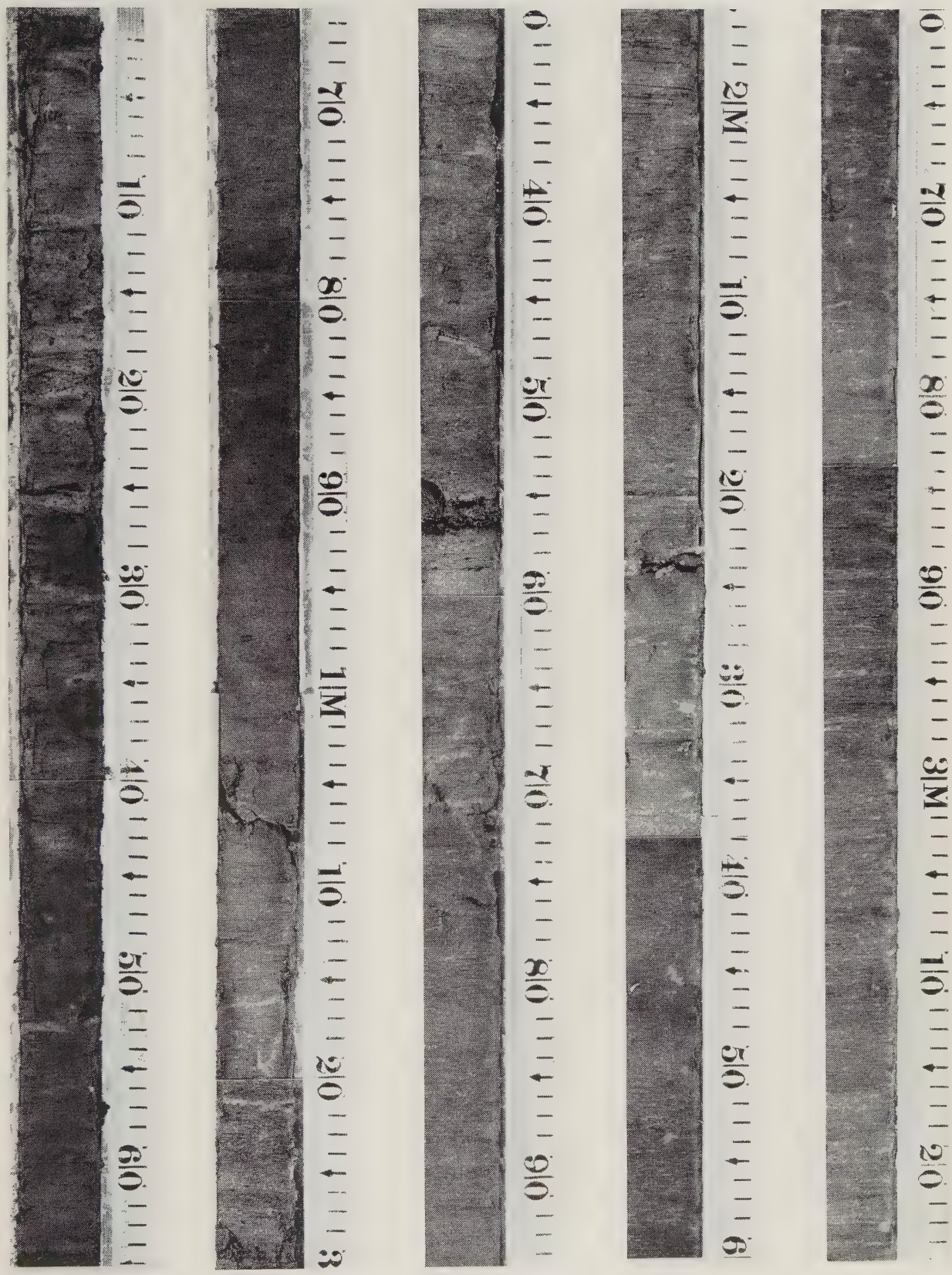

Fig. 25. Photos showing the continious core from Rödäng.

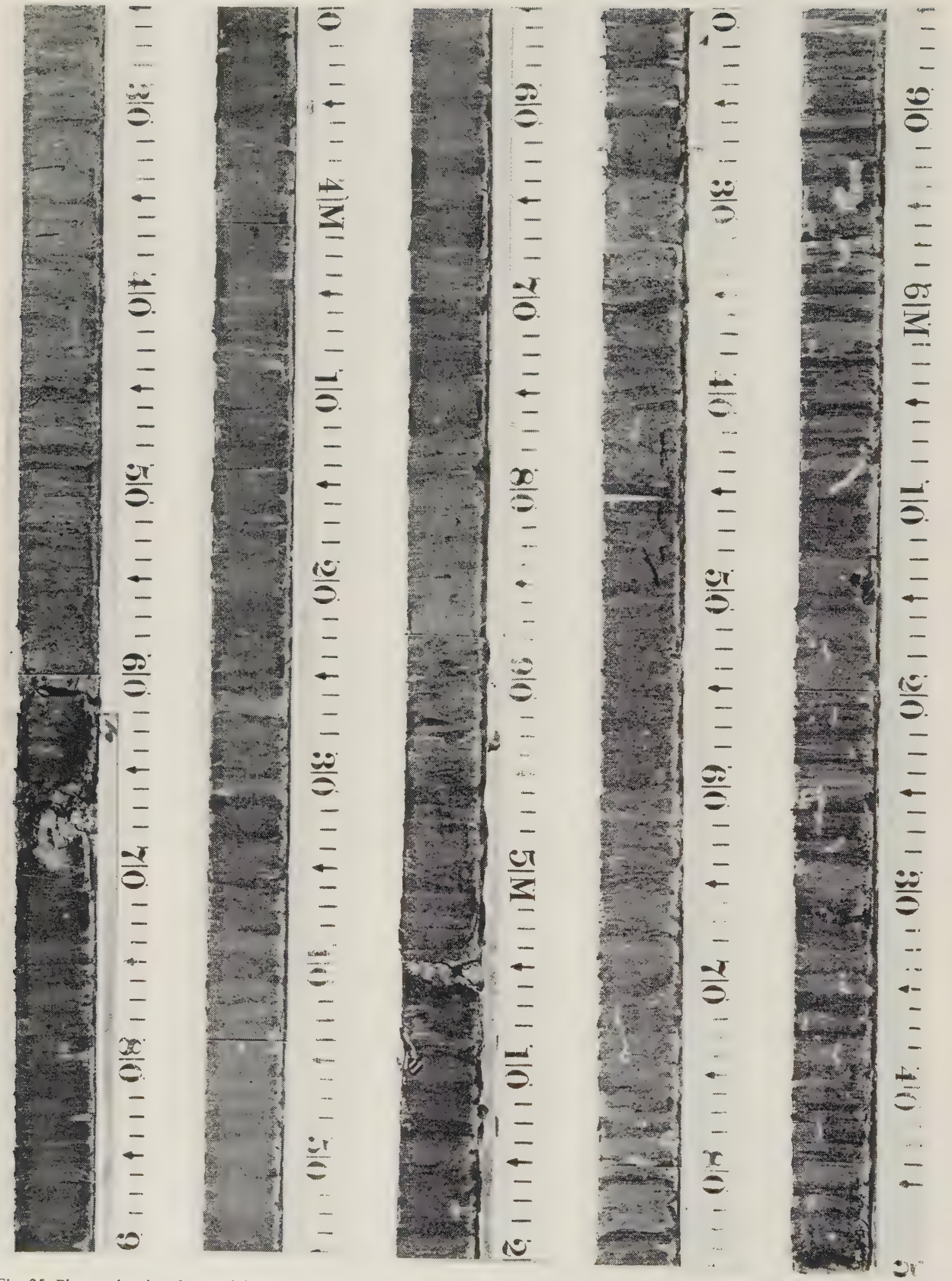

Fig. 25. Photos showing the continious core from Rödäng.

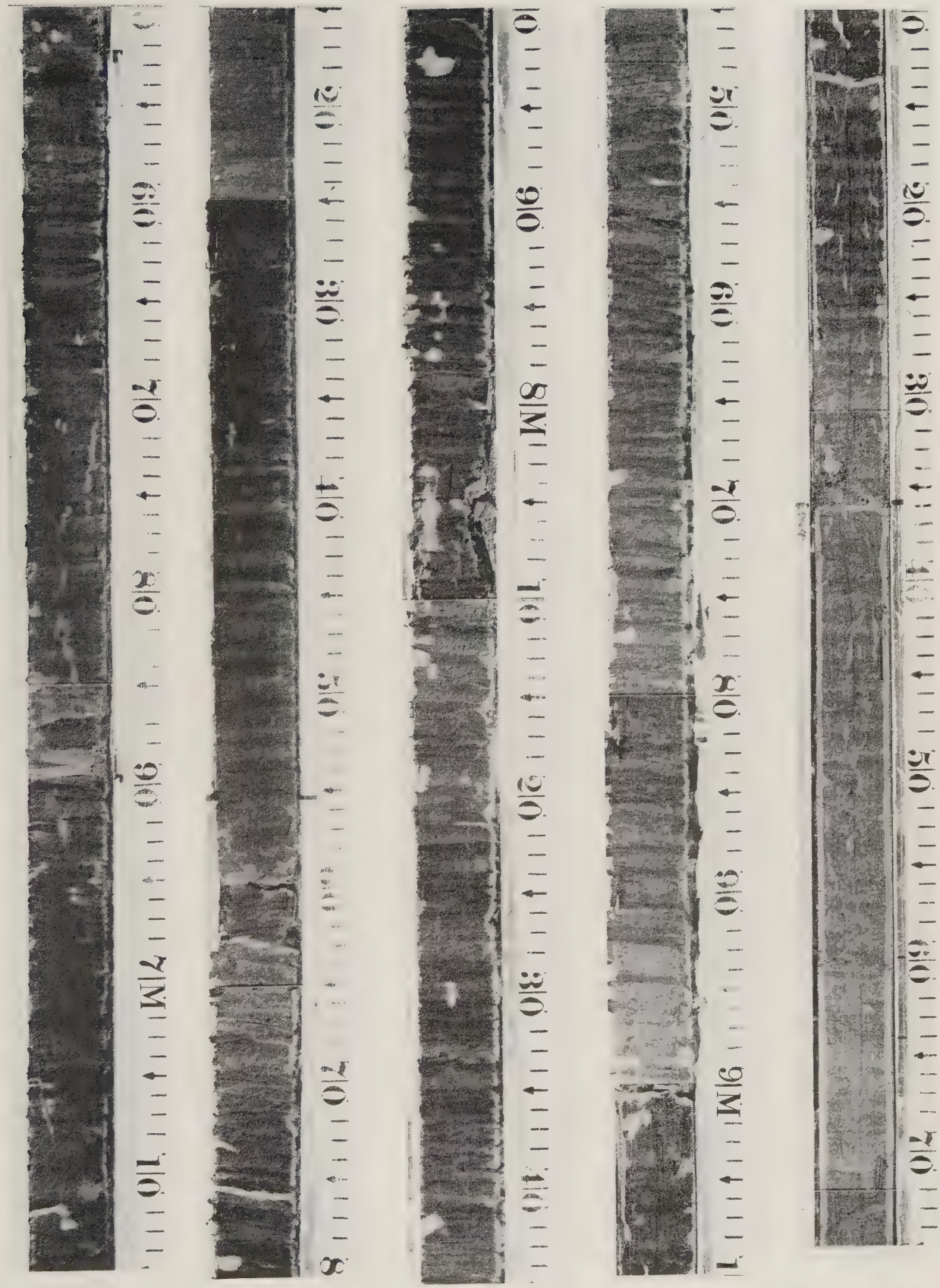

Fig. 25. Photos showing the continious core from Kodang.

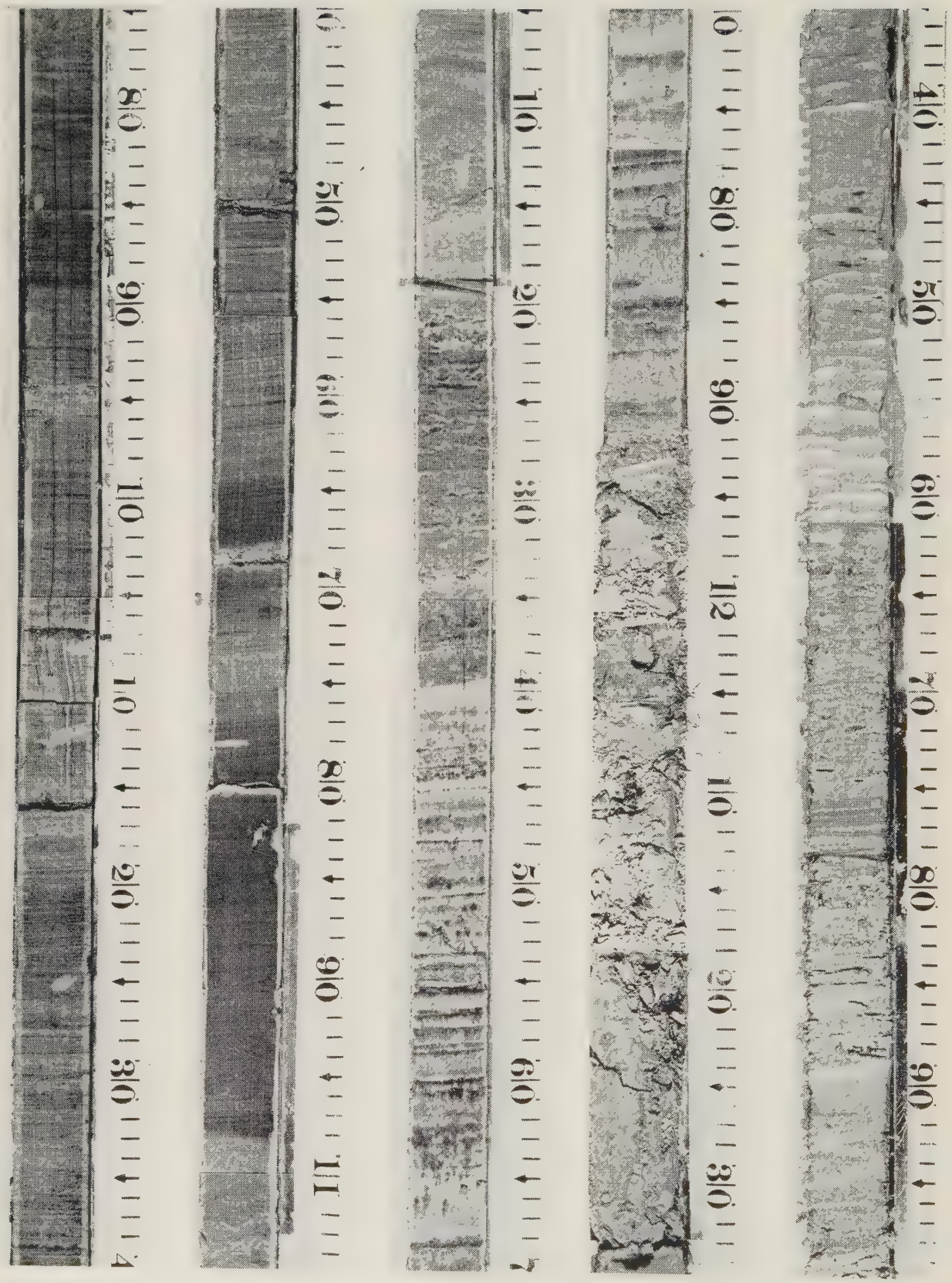

Fig. 25. Photos showing the continious core from Rödäng.

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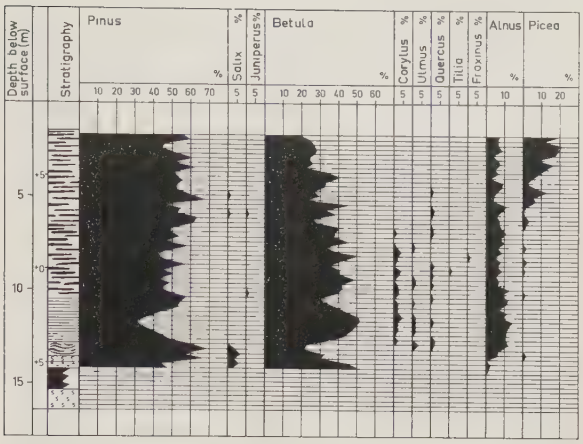

Fig. 26. Pollen diagram from Rödäng.

with those from diverse localities in Norrbotten according to Fromm (1965), and from Bodsjö bog (Wenner 1968), the Adak sediments (G. Lundqvist 1957), and the Lake Prästsjön sediments (Englemark *et al.* 1976). The last three sections were also dated by radio-carbon.

At Rödäng the *Picea* curve starts about 5.4 m below the ground surface, and the *Alnus* curve at about 13.4 m. According to the datings of, and correlations with, G. Lundqvist's (*op. cit.*), Wenner's (*op. cit.*), and Englemark's (*op. cit.*) sections, these occurrences could be assigned an age of about 3 000 B.P. and 8 800 B.P. respectively. The mean sedimentation rate within the Rödäng core could then be calculated as approximately 1.8 mm/year in the *Picea* "period" and 1.4 mm/year in the period between A° and P°. This latter value is very rough, since the lower section of the Rödäng core is inhomogeneous, being composed of four different types of sediment. Furthermore the degree of compaction, due to the overburden sediments, will vary throughout the section, thus distorting the values.

However, from the surface down to a depth of 10.5 m the sequence is comparatively homogeneous (except for some 0.1—1 cm thick layers of fine sand, see Fig. 27), which indicates that the sedimentation was fairly constant at an estimated 2 mm/year. This is in accordance with rates deduced from studies of comparable sediments in the Baltic (see, *inter alios,* Ignatius 1958).

This core from Rödäng will be discussed and compared with Fromm's (*op. cit.*) account of his investigations from Norrbotten, including micro-fossil determinations.

As the glacial clay shows distinct varves, it is unprobable that the water was very salt in the intracontinental sea during the deposition. The layer of grey clay with black grains presumably incorporates the last Preboreal birch maximum. This approximately corresponds to an age of 9 000 B.P. and according to Fromm (*op. cit.*) both fresh and brackish diatoms are present. At least the lowest layer of this section must reflect a deposition environment of somewhat salt water. The overlying grey clay with black bands most likely reflects the Boreal pine maximum during the Ancylus stage. Ignatius (1958) assigns this section to the Lower Ancylus.

The black upper part of the banded grey clay represents the transition between the Ancylus and the Littorina stages of few centuries after 7 000 B.P. During this period the climate was even warmer, the elm and the oak appeared, and the sea water became brackish in the Gulf of Bothnia.

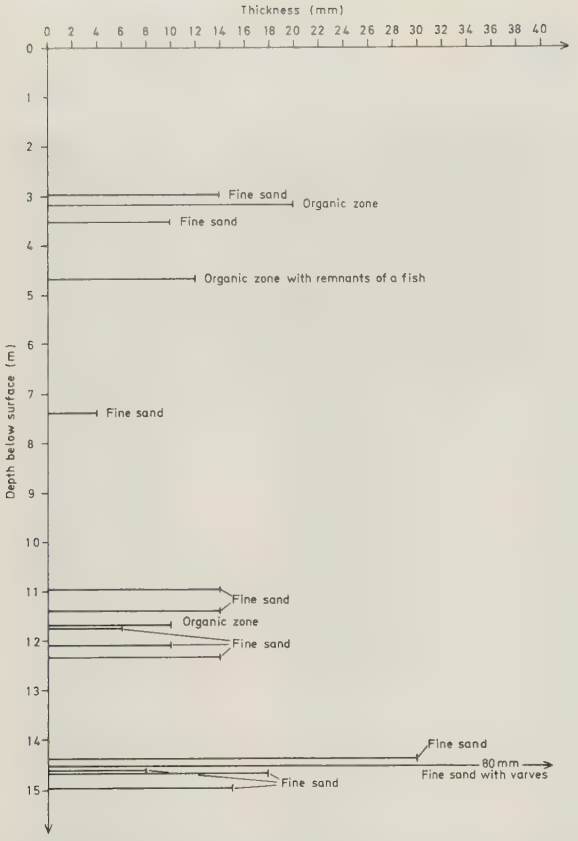
Thickness (mm)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
Depth below surface (m)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Fine sand
Organic zone
Fine sand
Organic zone with remnants of a fish
Fine sand
Fine sand
Organic zone
Fine sand
Fine sand
80 mm
Fine sand with varves
Fine sand

Fig. 27. Figure showing layers of fine silt and organic material found in the Rödäng core.

The shore line was about 100 m above the present level. A transition to the maximum of the post-glacial warm period is then visible in the micro-varved grey clay. During this period the mixed oak forest reached its greatest extent in Northern Sweden. Furthermore the birch presented the high and long maximum, between *c.* 7 000 and 5 000 B.P. The sea water was brackish and the shore line was 35 m higher than today. In the pollen diagram from Rödäng a distinct decrease in the amount of pine pollen and an increase in the birch pollen are visible in the micro-varved clay with black banding. This implies that this site was nearer the shore at the time when this part of the sequence was deposited. It possibly indicates a regression owing to the uplift of the land. Afterwards comes deterioration of the climate, a strong development of the spruce and a supposed regression of the upper tree line in the mountains, with a subsequent transition to modern conditions.

Grain-size distribution. — The modal fraction is the medium silt throughout the section. In the uppermost two m the percentages of clay and silt decrease. The decrease is reflected chiefly in the fine and medium silt fractions. The topmost part of these two metres may correspond to a stage when the Rödäng area was situated in a protected stretch of coast, with calm conditions for deposition. The main part of the Littorina sediments present an increase in the content of fine-grained material with increased depth. In the interval 7.5 to 10.5 m the clay content is almost constant while the silt diminishes. An increase follows, down to the grey clay with black grains. In the varved clay the fine-grained material diminishes. In the underlying silt layer the contents seem to increase. The grain-size distribution may be affected by several factors (cf. Discussion, p. 25).

According to the correlation matrix, Table 10, the amounts of clay and fine silt in these sediments are markedly correlated with the depth, at 0.75 and 0.65 respectively. This is due first and foremost to the general upwards decrease of the contents of clay and fine silt, depending on changing conditions during the deposition of the sediment. The distinct correlation of shear strength with clay and fine silt content is of interest as the cohesion of a soil depends on the power of attraction between the particles. These forces increase with decreasing distance. A low void ratio of a homogeneous clay thus has greater cohesion than a homogeneous clay with a high void ratio (cf. Hansbo 1975).

Water ratio and bulk density. — The water ratio and bulk density give a good idea of, *e.g.*, the porosity and the organic content of a sediment (cf., *inter alios*, Hansbo 1975).

The water ratio is significantly correlated with seven other parameters. The correlations are presented in Table 11.

Table 11. Rödäng: correlation coefficient (r) and significance (s) with respect to water ratio. N denotes the number of observation pairs.

	r	s	N
bulk density	−0.83	0.1	33
medium silt content	0.62	0.2	22
carbon content	0.53	0.9	23
exchangeable iron	0.79	0.1	23
exchangeable magnesium	0.63	0.1	23
exchangeable sodium	0.66	0.1	23
exchangeable calcium	0.82	0.1	23

These correlations refer only to the interval 1.43 to 12.65 m in the sequence. The lowermost layers are not described because the pairwise analyses were too few to yield significant values. The data are divided in order to obtain comparable values by reason of uniform environments (cf. p. 14).

The content of organic matter in a sediment influences the physical and the chemical properties owing to the capacity of the organic constituents to bind large quantities of water. The mechanism also involves adsorption processes, exchange reactions, and chelations (cf. Brooks 1972). As the density of organic matter and water is less than that of the mineral part (solid state) of a soil volume, the density of a soil with high contents of organic matter and water is lower than that of a soil with less organic matter and water. The greater content of soil water causes a greater pore volume. The water ratio, furthermore, depends on the grain-size distribution, the stress-strain conditions within the sediment, and chemical activity such as, *e.g.*, the carbon-dioxide production and the oxidation/reduction processes. Not only these factors but also the position in the terrain, the infiltration and drainage, and the overburden must be taken into account when the water-content values of a sediment are interpreted.

The water ratio increases by about 15—20 per cent about 4 m below the surface. Between 4 and 10 m the values range from 70 to 80 per cent. The bulk density accordingly decreases by about 0.2 g/cm^3 to values between 1.5 and 1.6 g/cm^3. It is evident that the ignition loss—con-

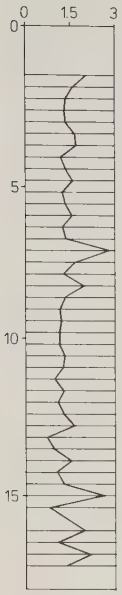

Fig. 28. Curve showing the ratios between the shear-strength determined in fall-cone tests and determined in unconfined compression tests.

firmed by the smoothed curves and the sulphur content—increases in this interval. The exchangeable ions show a marked increase simultaneously with the water ratio. This is particularly true of the exchangeable iron and the exchangeable calcium and is also visible in their good correlation with the water ratio. The water ratio declines in the lower parts of black micro-varved clay, grey micro-varved clay, black banded grey clay and lower grey clay. However, in the grey micro-varved clay and the fluid grey clay the water ratio still shows high values, about 60 per cent. In agreement with this the bulk density increases. In the glacial varved clay the water ratio is about 20 per cent. According to the water-ratio diagram the plasticity index (I_p) reaches its highest values in the intervals 4.5 to about 7.5 m and 9.5 to 13 m. The consistency limits will be discussed below.

The marked correlation between the water ratio and the amounts of exchangeable ions is secondary. The water content is determined by the porosity and the content of organic matter. These parameters are, in their turn, closely related with the grain-size distribution of the sediment. The divergences throughout the section are due chiefly to the variations in the environment during the sedimentation.

Undrained shear strength, fall-cone tests and unconfined compression tests. — The shear strength increases more or less linearly down through the sequence and the two methods agree on its distribution. Nevertheless, the shear strength determined by the fall-cone tests generally shows higher values. In the uppermost 6.5 m the shear strength remains fairly constant at 24 kPa and 16 kPa, respectively depending on the method used. The micro-varved clay and the grey sulphide-banded clay reveal an increase to about 30 kPa with both methods. The fall-cone tests, however, here show somewhat lower values. The fluid grey clay was examined only via the fall-cone test; the undrained compression test was not applicable to this sediment and the shear strength is very low, less than 10 kPa. The increased values for the shear strength below about 6.5 m may be related to the decrease in the water ratio and the increase in the bulk density. In the glacial varved clay the shear strength is very high, more than 60 kPa. However, the unconfined compression test produces somewhat lower values. Shear-strength determinations of the glacial varved clays may be hazardous due to the great differences between the layers. The unconfined compression test is especially doubtful being established on a theoretical surface of failure of 45° in the sample.

The ratio between the shear strength determined in fall-cone tests versus unconfined compression tests is about 1.5. The ratios are illustrated in Fig. 28.

Sensitivity, fall-cone tests. — The sensitivity (cf. p. 12) was determined in order to estimate the susceptibility to disturbance. When remoulded the shear strength presents about the same distribution throughout the sequence with a slight increase downwards. However, at about 12.5 m in the black clay the remoulded shear strength is about twice that of the surrounding sediments. Moreover, at this level the liquid limit has an increased value. The remoulded shear strength is about 1/20 of that not remoulded. The sensitivity is about 20 within the core except for four layers. The uppermost situated about 2.5 m below the surface, has a sensitivity of about 35. The next, at a depth of 7.5 m, is a good 30. The thickest layer is found between 10 and 12.5 m, in the grey micro-varved clay. The lowest appears in the grey clay with black bands. The fluid grey clay has not been tested. Thus these layers are the most sensitive sequences within the core. The grey micro-varved clay and the grey sulphide-banded clay, however, are more susceptible to disturbance.

Fall-cone liquid limit. — The consistency limits were determined for the liquid limit and the plasticity limit. The values of consistency limits are dependent on the water binding capacity of the soil in a remoulded state. The waterbinding capacity depends primarily on the content and kind of clay minerals and organic colloids, but the electrolyte contents of the pore water are also of importance (cf. p. 10 and Karlsson 1977).

The fall-cone liquid-limit distribution is similar to that of the ignition loss. The sediment is to be classified as a high plastic in almost the entire sequence, with one minor exception in the grey micro-varved clay. The plasticity index, however, gives a more differentiated distribution.

Plasticity index. — According to the plasticity-index determinations the sediment will be designated a medium-plastic. But the index reaches the limit for high-plastic clay in some parts of the sequence. The differences in the results from these two methods of determining the plasticity properties of a soil are mainly to be found in the performance. Nevertheless both methods are influenced to a high degree by a careful execution of the tests. This is to a great extent due to the colloidal activity within the sediment and the thixotropic properties.

pH. — In the main part of the sequence the pH values are 8 ± 0.5. In the upper 2.5 m, however, the pH shows a decrease towards the surface, from 8 to 6. Judging by the colour and odour of the sediment a reducing environment should exist within the main layers of the sequence. As stated above (see p. 5) the reducing conditions lead to an increase of the pH. The said decrease in the uppermost layer of the section may be an effect of the oxidation in the dry crust and the impact of Man. The pH is discussed in detail on pp. 5 and 13.

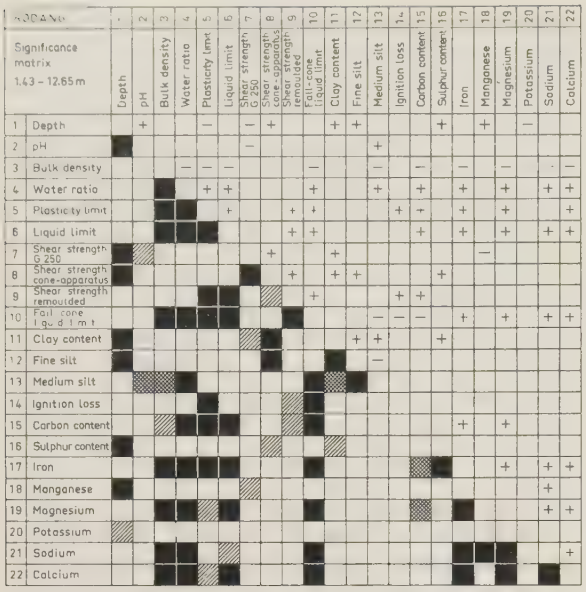

Fig. 29. Matrix showing the significance of the ocrrelation tests from Rödäng.

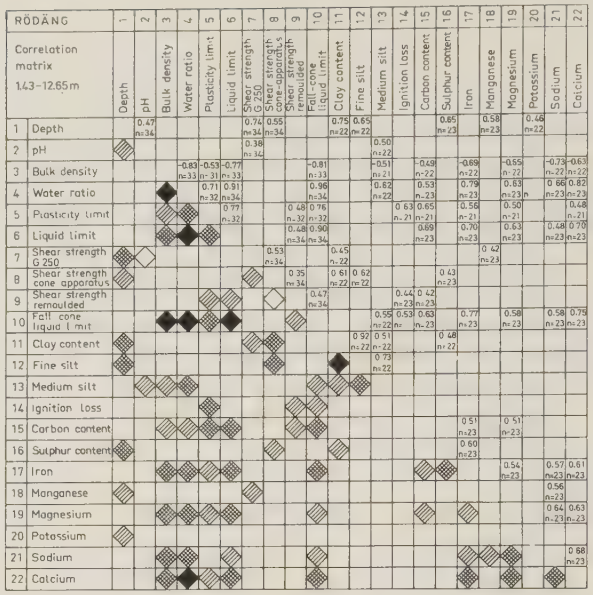

Fig. 30. Correlation matrix showing the interrelationships of the parameters studied in Rödäng.

Ignition loss and carbon content. — The curves for the ignition-loss and carbon-content are similar throughout the sequence. The agreements are particularly close in the case of the smoothed curves. The carbon-content curve shows a rising tendency toward the top of the section, although, fluctuating. This may reflect the evolution during the Littorina stage. The older parts of the core may to same extent reveal a higher degree of decomposition of the organic compounds. In the main part of the sequence the values range between two and a good three per cent.

The ignition loss shows values of 4 to 5 per cent. Nevertheless there are extremes of 7.5 and 7.3 per cent at 9.3 m and 12.4 m, respectively. In the interval 6.5 to 9.5 m the values are higher, fluctuating between 4.5 and 7.5 per cent. This interval was deposited during the Littorina stage in the evolution of the Baltic. Within the grey silt layer and the fluid grey clay with black grains the ignition loss values are somewhat less than 1.5 per cent. In the glacial varved clay the contents fluctuate about 2 ± 1 per cent.

Ignition loss and carbon content are distinctly correlated only with the water related parameters. A more detailed discussion of problems related to the ignition loss and the carbon content is found under Gammelgården (p. 25).

Sulphur content. — The sulphur is chiefly derived from the water at deposition and transported with the organic matter. As sulphur is an essential nutrient for all life, being a constitutent of proteins and many enzymes which play key roles in metabolism, living organisms—particularly microorganisms—change physicochemical environments (pH and Eh) which determine stability fields for sulphur minerals (cf. Garrels & Naeser 1958, Garrels & Christ 1965). The sulphur is distinctly and positively correlated with the depth. It may have been primarily more or less constant in the entire sequence. The general increase downwards may be an effect of the slight compaction.

The correlation with the clay content is moderate but significant. Furthermore, there is a moderate correlation with the shear strength. The correlation with the iron is distinct and negative. It must be remembered that the sulphur value represents total content, while the exchangeable iron alone was determined. As the iron sulphides may chiefly consist of the metastable monosulphides, the iron will at least to some extent become oxidized and dissolved during extraction (cf. p. 14). The stable pyrite, on the other hand, will not be dissolved. In the grey micro-varved clay there is a marked decrease in the iron content and a sharp rise in the sulphur content. This is certainly due in part to the occurrence of pyrite.

Exchangeable ions. — In principle iron, calcium, and potassium present similar curves. This appears especially clear in the smoothed curves. The agreement of the curves is visible for magnesium, manganese, and sodium. It is not significant, however.

From the correlation matrix (Figs. 29 and 30) it is evident that iron, magnesium, sodium, and calcium are on the whole significantly correlated with the same parameters. They are all markedly and negatively correlated with the bulk density. This seems natural as the pore volume and/or the content of organic matter decreases with increasing bulk-density. As the exchangeable ions are composed of the ions present in the interstitial water and those loosely bound to the clay minerals and organic compounds (cf. Løken 1970) a decrease in the amount of water will reduce the content of ions. Accordingly the correlation test reveals distinct correlations with the water ratio for all these ions. In pore waters of marine sediments under anaerobic conditions the iron can be dissolved and present in reasonably high concentrations in equilibrium with iron compounds as Fe^{2+}_{aq} (Wedepohl 1970). Iron and magnesium are moderately and equally correlated with carbon. The correlation of iron with magnesium is moderate and positive. Furthermore iron shows a distinctly negative correlation with sulphur. Thus the distribution of the determined elements agrees fairly well with the water ratio, the bulk density, the carbon content, the ignition loss, and the amount of fine-grained material.

As these ions are closely associated with the water con-

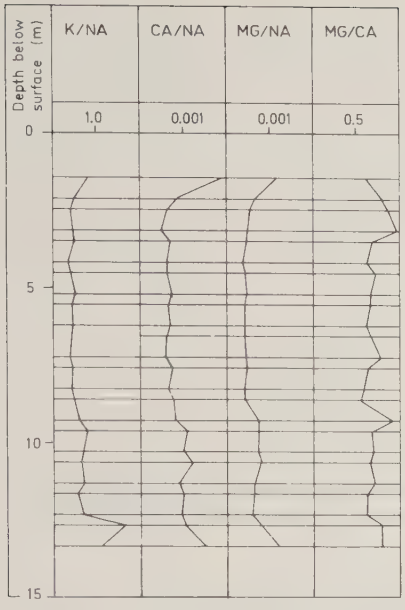

Fig. 31. Curves showing the ratios between the contents of exchangeable ions potassium/sodium, calcium/sodium, magnesium/ sodium, and magnesium/calcium.

tent and the organic matter they presumably reflect the conditions in the sea during the deposition regardless of secondary effects in the sediment, in the form of microbiological activity, migration, weathering, leaching, dilution and ion exchange. These effects, however, exert a minor influence.

In conformity with the discussion concerning the ratios between the exchangeable ions at Gammelgården (p. 29), the corresponding ratios were calculated for the Rödäng core (Fig. 31). Judging by the relative salinity changes within the core from Rödäng, the exchangeable ion ratios, potassium/sodium, calcium/sodium, and magnesium/ sodium may reveal an evolution beginning with fresh or relatively fresh water conditions in the bottom layer. The water then gradually became more saline and between 8.5 and 3 m the environment was probably brackish while the uppermost layers show higher ratios, indicating the presence of fresh water. The ratio magnesium/ calcium, however, does not show any clear trend. The curve allows no scope for conclusions concerning the water conditions during the deposition.

Conclusions. — The characteristic features of the sediments from Rödäng are:

the pitch black colouring of the fresh Littorina sediments disclosing on drying, however, a black banding showing, in addition to the banding of the sediment, varves 1 mm wide,

the odour on drying of the Littorina sediments,

the fluid grey clay and silt, underlying the Littorina sediments,

the low shear-strength properties and the high sensitivity.

The bed sequence reveals an evolution from the glacial varved clays at the bottom, via the transition between the Ancylus and the Littorina sediments, to the Littorina sediments at the top. The main part of the sequence consists of sediments deposited during the Littorina stage. The mean sedimentation rate in this part of the section is estimated as about 2 mm/year, calculated from comparisons between the rational limit of *Alnus* and *Picea* in the pollen diagram and comparative pollen analyses and ^{14}C dated seqences from neighbouring sites.

The shear strength determined in fall-cone tests shows values of about 20 kPa in the upper layers of the sequence, slightly increasing downwards to about 30 kPa. The unconfined compression tests, however, show lower values. In the fluid grey clay the shear strength is very low, about 5 kPa. The susceptibility to remoulding is very high and the sediment is chiefly medium-plastic.

The pH determinations, the colour, and the odour of the sediment implies reducing environments within the Littorina section. The ignition loss and the carbon content show the distribution to be expected from the general knowledge of the evolution of the Baltic, and from the changes of the climate indicated by the pollen diagram. The organic production increased during the Littorina stage. The sulphur content remains fairly constant throughout the sequence. The distribution of the exchangeable ions determined—especially considering the presented ion ratios—shows the expected evolution of the Baltic. The top and bottom layers may have been deposited in fresh or fairly fresh water while the bulk was laid down in a more or less saline or brackish environment.

Dynäs, cores A and C

Stratigraphy and some general aspects. — As to the details of the stratigraphy the reader is referred to Table 6.

The stratigraphy of this core shows good agreement with other stratigraphical descriptions from this area (cf. Jerbo 1965, Modig 1967, Ericsson 1971, 1973) and is easily correlated with other sections from the Bothnian Sea and the Gulf of Bothnia (cf. Fromm 1949, 1955, 1965, Ignatius *et al.* 1968).

The bed sequence reveals an evolution from the glacial varved clay at the bottom to the grey clay with black bands in the upper layers. In agreement with Fromm's (cf. p. 6) general sequence of strata the upper clay and the clay with micro-varves, some 0.7 m thick, partly remoulded, belong to the Littorina deposits. The underlying grey clay with black bands then probably corresponds to Fromm's section C (*op. cit.*) thus representing the transition between the Ancylus and Littorina stages. According to Fromm (*op. cit.*) this stage marks the first ingression of brackish water in the Gulf of Bothnia at the beginning of the Littorina stage.

The homogeneous, fluid grey clay, 7.83 to 7.97 m below the ground surface including an about 0.1 m thick layer of fine silt shows very low shear-strength properties. This section is thought to be the actual slip failure surface of the frequent landslides in this region (cf. p. 4). Some layers of fine silt and organic material were observed in this core. These observations are presented in Fig. 32. The shear-strength properties and the susceptibility to remoulding of these sediments will be discussed below.

Correlation tests with respect to depth were performed for the sections 1.18—7.60 m and 7.81—13.25 m below the ground surface. Table 12 illustrates the correlations within the first mentioned section.

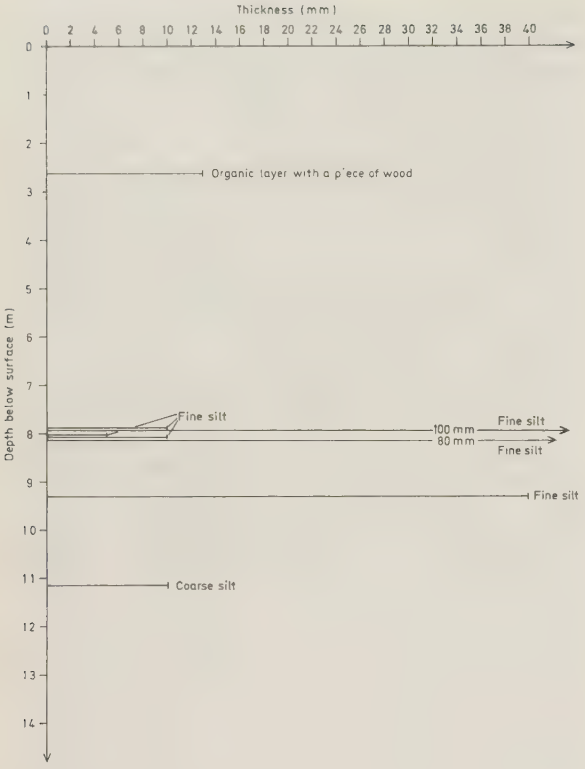
Thickness (mm)
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
Depth below surface (m)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Organic layer with a piece of wood
Fine silt
100 mm
80 mm
Fine silt
Fine silt
Fine silt
Coarse silt

Fig. 32. Layers of fine silt and organic material observed in a core from Dynäs.

Table 12. Dynäs, cores A and C, section 1.18—7.60 m; correlation coefficient (r) and significance (s) with respect to depth. N denote the number of observation pairs.

	r	s	N
water ratio	0.77	0.1	19
shear strength (fall-cone)	−0.66	0.2	19
bulk density	−0.83	0.1	19
medium silt content	−0.89	1.9	6

While calculated for very few pairwise analyses the correlations are considered fairly reliable owing to the homogeneity of the sections investigated (cf. p. 45) and the high levels of significance obtained. The correlations do not agree with the results from the other two sites. The reverse sign for the shear strength, the bulk density and the medium silt may depend on differences in the sedimentation conditions or exposure of the sediments to hydrostatic pressure. The correlations with respect to depth for the interval 7.81—13.25 m below the surface show high numbers for the same parameters with the exception of the medium silt. In this interval, however, the strongly correlated parameters are more numerous (cf. Figs. 35a to 35d). These correlations are calculated on a very few pairwise analyses, but the significance is extremely high.

Many of the parameters correlated derive from exchangeable ion and total element analyses. The possible relationships to depth may primarily reflect environmental changes during the deposition of the sediment. Moreover, correlations of the shear strength and the bulk density with depth which are negative in the upper layers are positive further down.

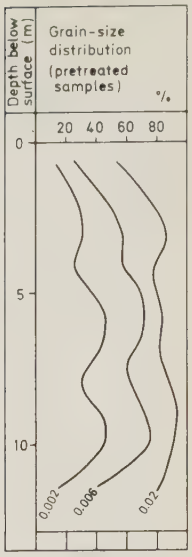

Fig. 33. Grain-size distribution determined on 11 samples pretreated to remove organic matter.

Grain-size distribution. — The clay content increases slowly from the surface down through the sequence. At the top it is 23 per cent. From a value of 26 per cent at about 7 m, in the grey clay with black bands, the clay content increases abruptly to about 44 per cent in the glacial varved clay. In the case of the silt fractions the percentages are comparatively constant in the upper layers with a decrease at about 6 m roughly coinciding with the clay content increase. In the glacial part of the sequence the silt fraction is about of the same order as in the upper layers.

As mentioned above (p. 10), a reference series of 11 samples, dried at 105°C, was pretreated with H_2O_2 to remove the organic matter. The results are shown in Fig. 33. For the uppermost 4 m, they show approximately the same contents as the "untreated" samples (see p. 20), but the silt fraction is smaller. Then there is a more differentiated distribution in the pretreated samples, especially as regards the clay content. The clay content is about 6 to 15 per cent higher in the pretreated samples, although fluctuating. The fluctuations seem to provide more convincing proof than the "untreated" analyses of a relationship between the distribution of some elements and, *e.g.*, the water ratio, the ignition loss and the clay content. In the case of the silt fraction there are only minor differences between "untreated" and pretreated samples. The distribution within the varved clay, however, below 10 m, diverges strongly from the results for the "untreated" samples. Both the clay and the silt contents are much lower in the pretreated samples investigated. These differences between the results of the pretreated and the "untreated" series may depend primarily on the high content of organic matter in the latter.

Water ratio and bulk density. — The water ratio for the postglacial parts of the cores ranges mainly between 60 and 80 per cent. Down to 4.5 metres the water ratio is fairly constant at 60 per cent except for the uppermost layer. In the interval 4.5 to about 8 m the ignition-loss values increase—this is reflected as an increase in the water ratio with maximum values of good 80 per cent with a corresponding decrease in the bulk density (cf. Fig. 14). The

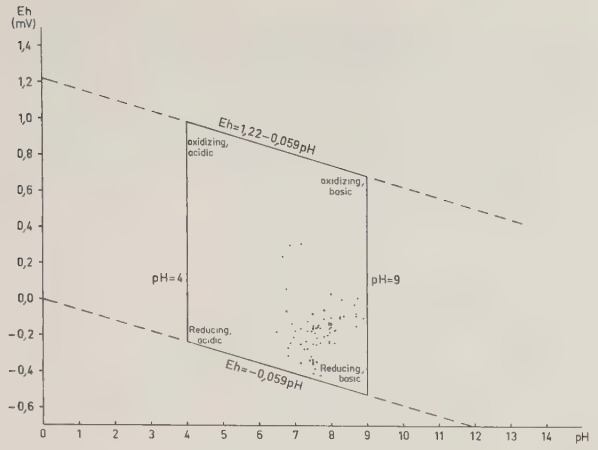

Fig. 34. The relationship between the redox-potential and the pH at different depths of the Dynäs core. For explanation see text.

similarity between the water-ratio curves and the curve of the ignition-loss values is very strong. But the correlation is not significant owing to the low number of pairwise analyses. Then there is a more or less linear decrease downwards in the glacial varved clay to about 20 per cent. The bulk density values range between 1.5 g/cm^3 and about 2 g/cm^3 and tend to show a distribution opposite to that of the water ratio and the ignition loss (cf. Fig. 14). The correlation coefficient between the water ratio and the bulk density is —0.77. Thus the highest values for the water ratio and subsequently the lowest for the bulk-density are found in the upper layers of the varved clay, the very loose grey clays, the micro-varved clay, and the lowest fourth of the black banded clay.

Undrained shear strength and sensitivity. — The shear strength determined in fall-cone tests shows high values in the uppermost and lowermost layers of the sequence. The top 2 m show shear-strength values in excess of 20 kPa owing to the influence of the dry crust and the vegetation. There are, however, great differences in the results. In the interval down to about 7.7 m the shear strength remains almost constant at about 17 kPa, although somewhat lower in the sparsely sampled core.

In the grey clay with black sulphide spots and the fluid grey clay together with the upper layer of the glacial clay the shear strength is low, 5 to 10 kPa. However, the sparsely sampled core shows lower values. This interval, thus, has very low shear strength, moreover the sensitivity is high, higher than 50. This agrees with the conditions applied to remoulded clay when classed as quick clays. It confirms the assumption from other investigations that this part of the sequence is sensitive to disturbance and presumably represents a latent slip surface. In the lower layer of the varved clay the shear strength is high. The remoulded shear strength is very low, about 1 to 2 kPa. This results in high values for the sensitivity. The fall-cone sensitivity exceeds 50 through all but the uppermost layer of the sequence. The sediment is thereby a quick clay according to the classification adduced on page 12. The sensitivity values are higher than 100 in most the sequence, with an extreme of 550 at a depth of 10.8 m. These high values for the sensitivity agree well with other investigations from neighbouring sites. Thus, when studying archieve material from the Geotechnical Department of Swedish State Railways, sensitivity determinations from the site Väja show a majority for values higher than 100, many over 400, with extremes of 770.

The results of investigations at Dynäs reflect the high susceptibility of the sediments, especially the fluid grey clay. However, a more objective method of estimating the sensitivity is needed when considering the properties of such sediment. The rapidity of the soil (p. 12) is certainly a better but so far not the ideal method.

The shear strength determined *in situ* by the field-vane apparatus demonstrates good agreement with the results obtained in the fall-cone tests. Nevertheless, a slight increase in the shear-strength values was observed in the interval about 5 to 7.5 m (cf. the clay content of pretreated samples discussed above). In this interval, the shear strength determined by the unconfined compression test has a similar increase to the water ratio, the carbon content and the exchangeable ions. The shear strength determined by the field-vane apparatus agrees closely with the fall-cone determinations from the sparsely sampled core and the unconfined compression test. The sensitivity determined in the field-vane tests, however, yields much lower values than those obtained in the fall-cone tests. In these the sensitivity exceeded 100 throughout the sequence while in the field-vane test the sensitivity is generally about 10 to 20 which is on a par with normal Swedish postglacial sediments. The field-vane tests were performed at a depth of 8.3 m.

The unconfined compression tests show good agreement with the fall-cone and the field-vane tests and no remarkable differences emerged.

Consistency limits, liquidity index, and plasticity index. — According to the fall-cone liquid limit the clay throughout the sequence is generally medium-plastic. Within a 1 m thick layer of the varved clay, the determinations show a low-plastic clay. In the glacial varved clay, however, determinations of consistency limits and sensitivity do not yield reliable results, owing to the inhomogeneity of the clay. The varves have widely varying properties as, *e.g.*, the water ratio, the grain-size distribution, the content of organic matter and of iron. The fall-cone liquid limit shows increased values in the grey microvarved clay in agreement with the increased values of the ignition loss.

Thus, there are differences in the results obtained for the fall-cone and the percussion liquid limit. The clay is classified as low-plastic according to the percussion liquid limit (given in terms of I_L) while in the fall-cone liquid limit it is medium-plastic. This investigation shows lack of precision in the methods for determination of the consistency limits and the sensitivity of these sediments (cf. Discussion of Rödäng p. 37).

The liquidity index is >1 throughout the sequence, the highest value determined being 11, about 9 m below the ground in the glacial varved clay. The remoulded clay, thus, will be defined as semi-liquid to liquid.

As seen from the water-ratio diagram the plasticity index, I_p, is generally less than 10. This means the clay will be designed low-plastic. However, the plasticity index is higher between 1.5 and 2 m below the ground, and in the micro-varved clay down to the upper layer of glacial varved clay. The value, consequently, approaches 15 and the clay is medium-plastic.

Ignition loss and carbon content. — The ignition loss is about 5 per cent within the Littorina sediment sequence.

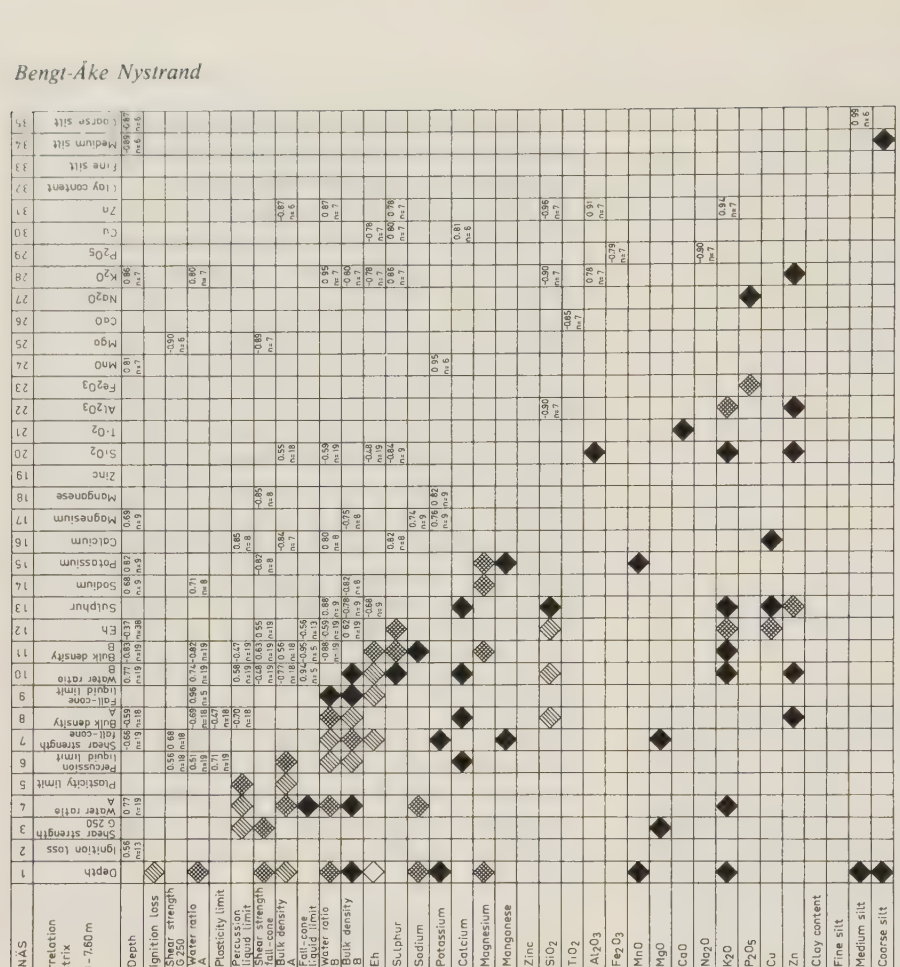

Fig. 35a. Matrix showing the significance of the correlations tests in the sequence 1.17 to 7.60 m, Dynäs.

Fig. 35b. Correlation matrix showing the interrelationships of the parameters studied in the sequence 1.18–7.60 m, Dynäs.

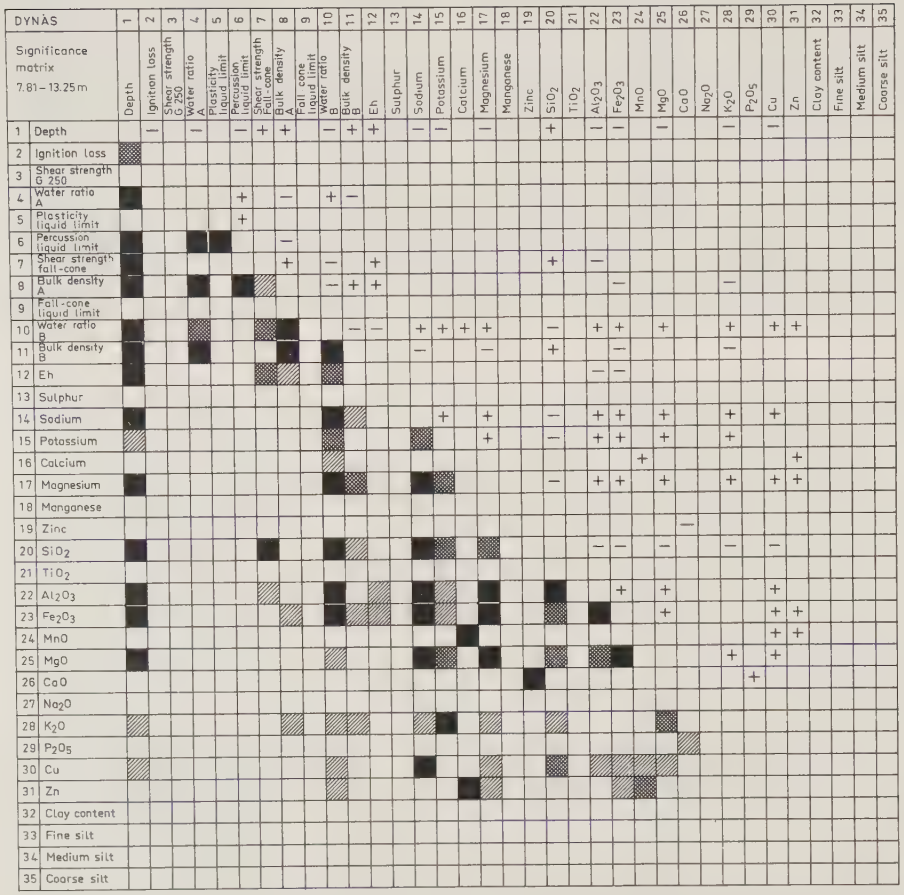

Fig. 35c. Matrix showing the significance of the correlations tests in the sequence 7.81 to 13.25 m, Dynäs.

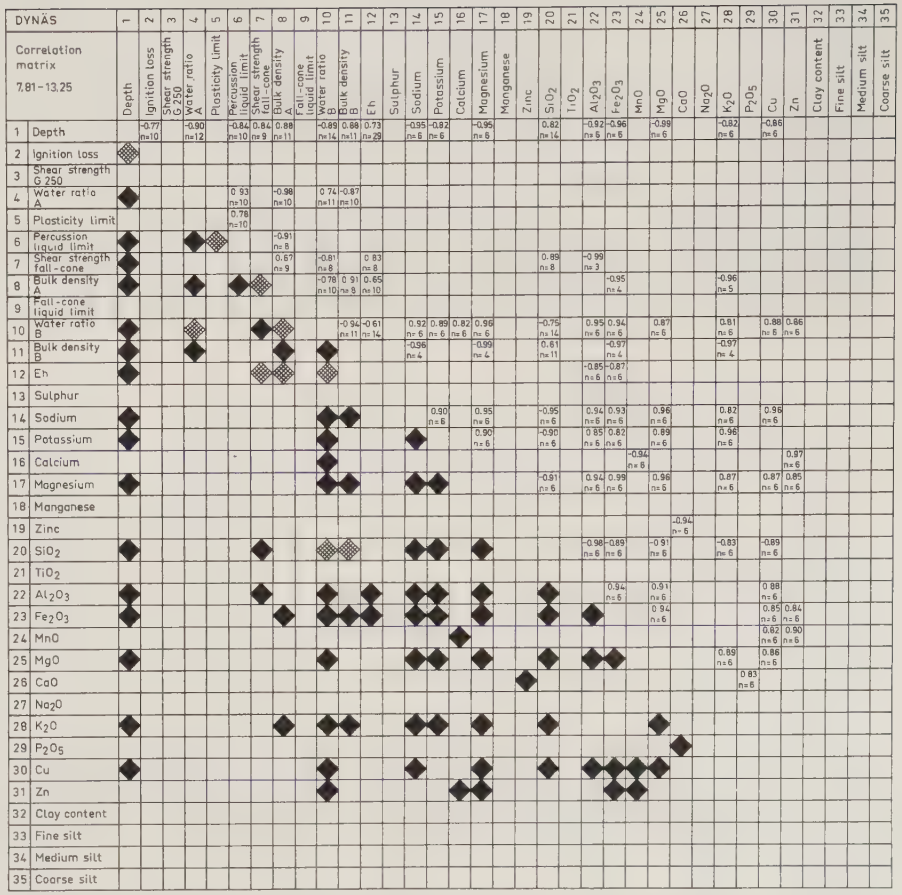

Fig. 35d. Correlation matrix showing the interrelationships of the parameters studied in the sequence 7.81–13.25, Dynäs.

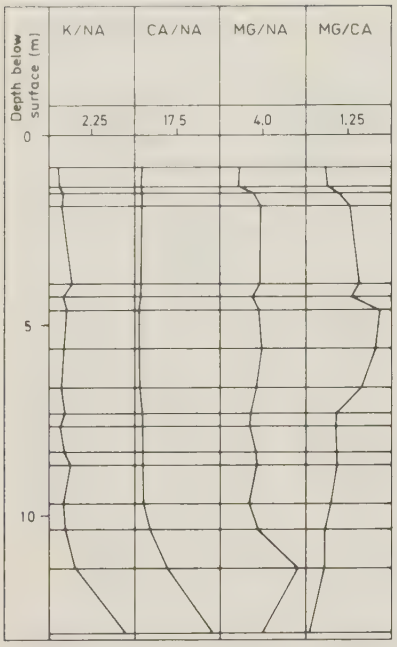

Fig. 36. Curves showing the ratios between the contents of exchangeable ions potassium/sodium, calcium/sodium, magnesium/sodium, and, magnesium/calcium.

But there is a sharp increase in the lower layer of the grey clay with black bands and in the grey micro-varved clay, down to the fluid grey clay, 4.5 to about 8 m below the ground. In the fluid grey clay the content is about 2 per cent and in the glacial section of cores A and C there is a decrease downwards from 6 to about 0.6 per cent. The carbon-content distribution closely resembles that of the ignition loss. The carbon content is about 1.5 per cent in the Littorina and Ancylus sediments apart from the interval 5 to 7.5 m in which the highest values approach 2 per cent. This increase therefore coincides with the ignition loss. The ratio between the ignition loss and the carbon content generally ranges between 2.3 and 2.8 throughout the section. The ignition loss and the carbon content are not distinctly correlated to any other parameter determined. The reason is the very low number of pairwise analyses. The ignition loss and the carbon content in general are treated in the discussion of Gammelgården (p. 25).

Sulphur content. — The sulphur content is low throughout the sequence, about 0.2 to 0.3 per cent in the Littorina and Ancylus sequences and about 0.1 to 0.2 per cent in the glacial deposits. At 7.5 m below the surface, however, the sulphur content approaches 0.8 per cent, in the lower grey clay with black bands.

The cause of the low sulphur values may be the following. The sulphur is strongly bound to iron in the form of pyrite. According to Barnes & Kullerud (1961) pyrite is stable up to 625°C and above this temperature pyrrhotite (FeS) and hematite (Fe_2O_3) form a stable association. This means that the method used for sulphur determinations will not reveal the strongly bound sulphur. Referring to the discussion of the colour of the sediment (cf. p. 5) this supports the theory that the grey colour reflects a situation where the main part of the sulphide is in the form of the stable pyrite.

According to, *e.g.*, Papunen (1968) and Ignatius *et al.* (1968), pyrite is found in sulphide-rich soils, even as pyrite spherules in a narrow zone in the upper Ancylus clay.

The sulphur is distinctly correlated to the water ratio, the bulk density, and the Eh. These correlations may reflect environmental conditions where in the main monosulphides are present.

Dynäs, core B

Water ratio and bulk density. — The water ratio and the bulk density are in good agreement with the determinations from cores A and C. In core B, which was analysed in greater detail there is a very marked difference between the glacial and the postglacial deposits (cf. Fig. 15). Furthermore, the water ratio demonstrates lower values in the upper layer of the varved clay than in cores A and C and, consequently, the bulk density here boasts higher values.

Shear strength and sensitivity, field-vane apparatus. — The shear strength determined *in situ* by the field-vane test shows a distribution almost identical to that determined in hole number 17, Fig. 13. The sensitivity defined by this test, however, demonstrates higher values and a somewhat different distribution. This may be an effect of greater uncertainty in the determinations of low shear-strength values, and the fact that a moderate error in these determinations will greatly distort the sensitivity numbers.

pH and Eh. — The redox conditions and the acidity of the sediment were established by Eh and pH determinations (cf. p. 13). The pH approaches 7 in the uppermost layers of the sequence and increases linearly downwards to about 8 in the transition zone between the postglacial and the glacial deposits. The pH determinations consistently show higher values than those reached by Jerbo (1965) at a neigbouring site. Within the glacial varved clay the pH reaches the value of 9.

The pH and the Eh are plotted in Fig. 34. The dots in the centre of the diagram represent the topmost samples while the low potential and high pH valued dots in the lower right corner mark the interval of the grey silt, the fluid grey clay and the grey varved clay.

The environment within the sediment is reducing. The RPD zone in the sediment is about one metre beneath the ground, thus, on the whole coinciding with the upper boundary of the saturated zone.

Total contents of elements. — The SiO_2 shows an interesting distribution throughout the sequence. As the amounts of quartz and feldspars generally diminish strongly in the finer size fractions, a differentiation with regard to particle-size distribution is often reflected in the silica content of a sediment (cf. Soveri 1950, 1956). The clay minerals, transported long distances in suspension, are predominant in fine-grained sediments deposited in calm environments. The coarser sediments, richer in quartz and feldspars, settle in shallow water with greater transport capacity.

In the upper layers, down to about 7 m the SiO_2 content is fairly constant at about 500 mg/g, while in the interval 7 to 10.5 m, representing the grey clay with black bands, the grey clay with black sulphide spots, the fluid grey clay and the upper part of the glacial grey clay, it fluctuates between

200 and 400 mg/g. This interval probably represents a period with a deeper and calmer water deposition environment. As seen from the grain-size distribution curves, the clay content increases and the silt fraction declines in this interval (cf. Al_2O_3 below).

In sediments, TiO_2 may be contained in minerals such as ilmenite, rutile, anatase, brookite, sphene, biotite, amphiboles, and pyroxenes (Degens 1965). The bulk of titanium is bound to the clay fraction, explained by the interaction of clay minerals with amorphous or finely dispersed crystalline titanium oxide or titanium-dioxide hydrate released during weathering (Degens *op. cit.*).

According to Fleischer's (1955) extensive review of the literature on trace and minor elements found in sulphide minerals titanium appears as a trace element only in pyrite. He reports maximum contents of 600 ppm while the most common contents were 200 to 500 ppm in 21 samples considered. In this investigation the titanium contents are about 2 and 4 mg/g, thus exceeding the contents reported by Fleischer.

The Al_2O_3 contents within the Littorina sequence are fairly constant, 200 mg/g. In the interval from about 7 to 10.5 m there is an increase to about 300 mg/g coinciding with the decrease in the SiO_2 content. The Al_2O_3 increase, thus, corresponds well with the increase in the clay content. The illites, the dominating clay-mineral group in Swedish Quaternary clays, contain a slightly variable but always high content of alumina, about 20—29 per cent (Grim 1968, Appendix; Wedepohl 1970). The alumina content of chlorite, another component in Swedish Quaternary clays is slightly lower, 15 to 25 per cent (Grim *loc. cit.*, Wedepohl *op. cit.*). Tamm (1920) and Salminen (1935) concluded that the most fine-grained clays have the lowest SiO_2 and the highest Al_2O_3 content.

The Fe_2O_3 analyses show increasing values down through the sequence to a depth of about 8.5 m in the glacial varved clay. Down from this level there is a continuous decrease in the iron content. In the grey clay with micro-varves an abrupt decrease is observed. The iron distribution in the sequence closely agrees with that of the clay content. This is intelligible with regard to the occurrence of iron compounds, such as chlorite and iron sulphides, preferably in the finer size grades. The ignition loss, the carbon-content, and the water-ratio distribution manifest strong similarities to that of the iron content.

The *MnO* distribution closely resembles those of Fe_2O_3, *MgO*, and *Zn*. The iron and the manganese generally have similar distributions in sediments and the Mn/Fe ratio is commonly 0.02 (Wedepohl 1970). In this investigaiton this ratio is 0.02—0.03 on average. The manganese distribution too is often comparable with that of zinc, as the Mn^{2+} and the Zn^{2+} are similar in ionic size and thought to alternate in the crystal lattice. The curves of MnO and Zn in fact show certain similarities. Like the exchangeable manganese and zinc, the total contents, the MnO and the Zn, present a marked decrease corresponding to that of the SiO_2 in the interval 7.5 to 9.5 m. In this interval the clay content increases as the silt fraction diminishes. This supports the theory that the manganese is often present as coatings on the particles (cf., *e.g.*, Wedepohl *op. cit.*).

The *CaO* and the K_2O show fairly constant values of about 10 mg/g and 30 mg/g, respectively. There is, however, an increase in the interval with higher clay content, water ratio and content of organic matter. The Na_2O content increases downwards except for the marked decrease in the grey micro-varved clay and the topmost layer of the glacial varved clay. Furthermore there is one low value in the upper clay with black bands. There are no corresponding decreases in the amounts of exchangeable sodium.

Phosphorus is abundant in the earth's crust, with an average content of about 0.08 per cent, chiefly in the form of apatite ($Ca_5(F, Cl, OH)(PO_4)_3$). Moreover organic phosphorus compounds occur. Micro-biological decomposition of the organic matter releases phosphorus as phosphate ions (cf. Troedsson *et al.* 1973).

The P_2O_5 curve contains no features common to other curves. This may partly depend on the paucity of analyses.

The *Cu* content is low; increased values are found in those parts of the sequence with higher clay contents. This may depend on the fact that, via weathering released copper ions are firmly bound to clay minerals and/or organic matter and only a small amount is exchangeable (Troedsson *et al.* 1973).

Exchangeable ions. — The distributions of exchangeable ions all show close agreement with the water ratio, ignition loss and clay content. There are some deviations, however. The *manganese* shows low values in the upper layers of the sequence and in the upper stretch of glacial varved clay. The decrease in the upper part of the core may be due to the biological activity and, to some extent, environmental conditions during the deposition. The manganese decrease in the grey clay and the upper part of the glacial varved clay, however, can be correlated with the increase in the clay and the decrease in the silt content. Here exchangeable manganese varies in the same manner as the total content. The distribution of *calcium* diverges from those of, *e.g.*, the water ratio and the ignition loss. The main factors determining the calcium distribution are the water ratio and the contents of organic matter and clay. The distribution of exchangeable *zinc* closely resembles that of the total zinc content. The distribution of the manganese and the zinc are often compared, by reason of similarities in ionic size (see above) and the Mn/Zn ratios frequently calculated. According to Wedepohl (1970) the lack of an almost constant ratio in the sedimentary environment can be explained by the influence of the redox conditions on manganese. In conformity with the discussion concerning the ratios between the exchangeable ions at Gammelgården (p. 29), the corresponding ratios were calculated for the Dynäs cores (Fig. 36). The exchangeable ions may reflect an evolution from a fresh or fairly fresh water environment in the oldest part of the cores and a brackish or slightly saline stage in the bulk of the sequence. The uppermost parts of the ratio curves, however, are indifferent.

Dynäs, cores A, B, and C: statistical treatment

The analyses from the Dynäs cores were statistically processed (see p. 14) and the correlation matrices are given in Fig. 35a—d. The correlation analyses were performed in a statistically correct manner. The number of observations (N) is small, however. This depends on the fact—as stated above—that at Dynäs a great number of different analyses were performed on samples from three cores, A, B, and C. As the sampling frequency was not the same in the three cores and the sample size was restricted, the pairwise

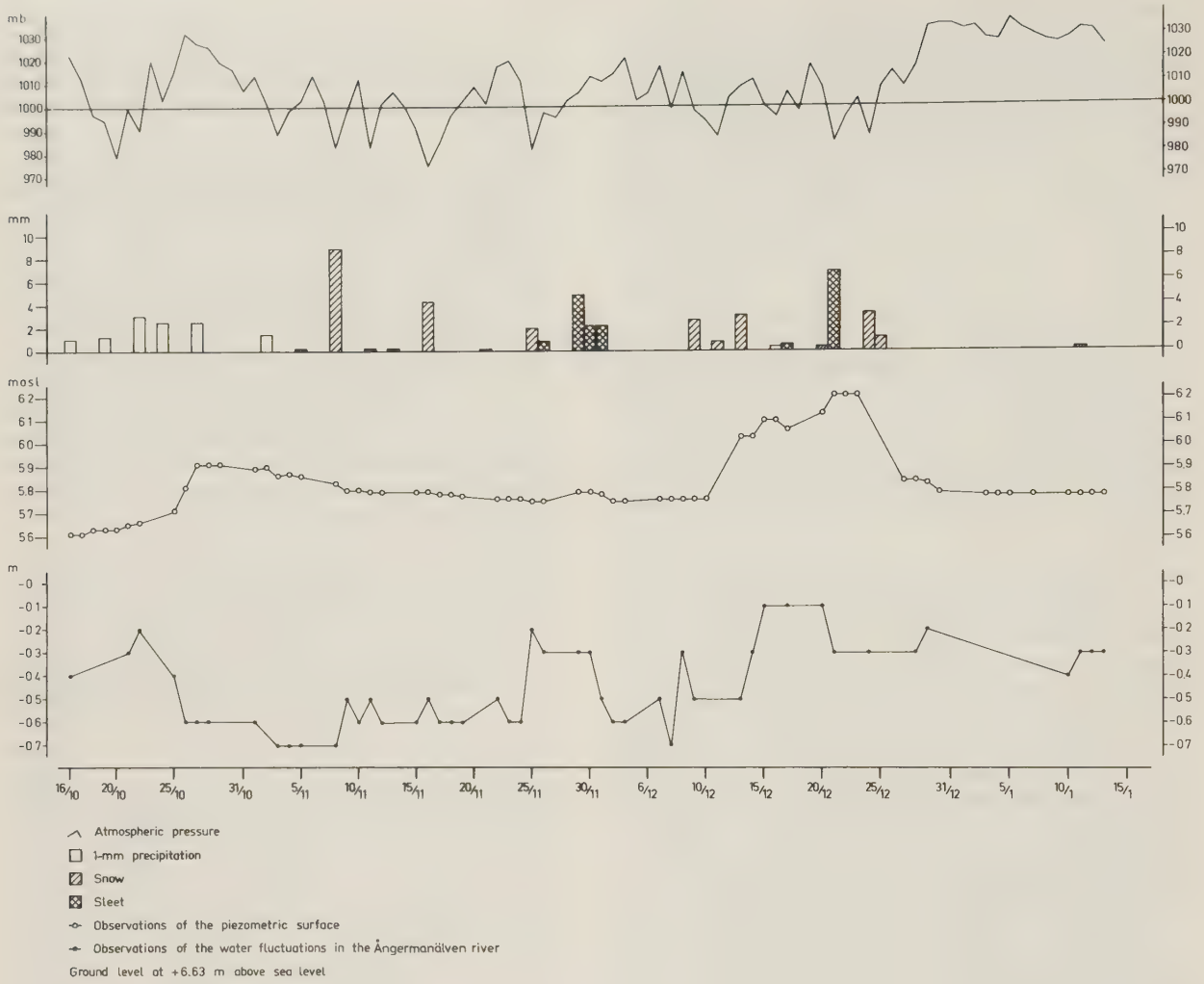

Fig. 37. Diagram showing flucutations of atmospheric pressure, precipitation, piezometric surface, and water surface of Ångermanälven river in the Dynäs area between October 16th, 1971 and continued 90 days.

values are few in number. The matrices, however, are considered reliable as relevant to uniform environmental conditions. Thus, separate matrices account for the postglacial and glacial sections of the cores.

Dynäs: observations of the piezometric surface

Observation of the piezometric surface commenced on October 16th, 1971 and continued for 90 days. The difference between the lowest and highest levels is 0.60 m. The observations are plotted in the diagram Fig. 37, which also contains data on air pressure and precipitation, received from a neighbouring weather observation station (Viksbäcken) of the Swedish Meteorological and Hydrological Institute (SMHI). Observations of the water-level of the Ångermanälven river were contributed by the Hammar pumping station nearby. Since the soil in which the observation tube is inserted is comparatively dense, the observations of the piezometric surface will not be stabilized during the first fortnight (cf., *inter alios*, Ward 1967), *i.e.* the comparison of the curves should cover the period 31/10 1971 to 13/1 1972. There is a tendency to reverse fluctuation of the air pressure compared with the water observations in the tube. A comparison of the water fluctuations in the river with those in the tube indicates similar development at least after December 10th, 1971. In order to assess the relationship between these four variables they were statistically tested via a computer program (cf. p. 14). This test shows that the air pressure is significantly correlated only with the precipitaiton, and naturally the coefficient is negative. However, the correlation coefficient is low, –0.41. The water-level observations in the tube are only significantly correlated with the fluctuations of the river. The correlation coefficient is low, 0.44.

There are obviously communications between water storage in the ground and the water in the river, even if the correlation is low (cf. Ward 1967). Air pressure and precipitation have no effect on the storage. The reason for non-correlation between the precipitation and the water level in the observation tube may be an effect of the climate, *i.e.* at the beginning of the period the precipitation was in the form of rain, later of sleet and finally of snow. This, in connection with freezing of the topmost layer of the soil cover, will create a barrier against the infiltrating

water. Hence during this short observation period, the interval 0.43 m to 1.03 m below the ground surface is affected by influent and effluent stages of the river. This will cause an alternating inflow and discharge of groundwater. Apart from changes in the pattern of the groundwater current, this will result in alternation of the effective stress in the soil. This interval may exceed 0.60 m during a long observation period.

Dynäs, conclusions

The characteristic features of the sediments at Dynäs are:

the grey clay with black bands and the micro-varved grey clay, beneath, in the Littorina section,

the odour on drying of the Littorina sediments,

the fluid grey clay including a fine silt layer within the Ancylus section,

the low shear-strength properties and in parts very high sensitivity.

The sequence reveals an evolution from the glacial varved clays at the bottom via grey fluid clays with fine silt layers, the transition sequence between the Ancylus and Littorina deposits to the upper section of Littorina sediments.

The shear strength within the sequence is low. Determined by unconfined compression tests it shows lower values than those determined with fall-cone tests or field-vane apparatus. In the fluid grey clay section the values are extremely low, 5 to 10 kPa. This section is thought to be the slip surface in the landslides which frequently occur in this region. The sensitivity determined in fall-cone tests is very high, more than 50 throughout the section. The field-vane tests show lower values for the sensitivity, 10 to 30. From the consistency-limit determinations the clays can be classified as low-plastic, according to the percussion liquid limit test and medium plastic judging by fall-cone liquid limit test. The carbon content and the ignition loss show high values within the Littorina sediments, 1.5 to 2 per cent and 5 to 8 per cent, respectively. The highest amounts of fine-grained material are found in the section 2 to 10 metres which coincides with the section presenting high values for the water ratio and increased values for the carbon content and the ignition loss. The sulphur content is low, generally less than 0.5 per cent. The SiO_2 shows an interesting divergent distribution in the section 7 to 10.5 metres, probably owing to changed deposition environments. The exchangeable ions may reflect an evolution from a fresh or fairly fresh water environment in the oldest part of the cores and a brackish or slightly saline stage in the bulk of the sequence. The uppermost parts of the ratio curves are, however, indifferent.

Final remarks

All three sites investigated, Gammelgården, Rödäng, and Dynäs, have black sulphide-bearing sediments. There are, however, great differences between the sites. The northernmost, Gammelgården, will not be compared with the other two sites, being very different as regards

the stratigraphy,

the grain-size distribution (coarser sediments),

the colour of the sediments (much deeper black),

the much higher contents of, *e.g.*, iron, manganese and sulphur,

the discussed vertical fissuring with thin hydroxide coatings,

the higher water ratio and the lower bulk density,

the higher carbon contents and ignition loss values.

At Gammelgården the main factors influencing the distribution of extractable iron and manganese in the sediments are the organic matter distribution, the water ratio and the grain-size distribution. However, these parameters are to a great extent dependent on each other and ultimately on the environment during the deposition. The environment within the sediment, especially in the uppermost layer, is influenced by biological activity and changes of level in the piezometric surface.

The curves of the exchangeable ions show distributions similar to those of, *e.g.*, the water ratio, the organic matter, and the grain-size distribution. The curves from Gammelgården, however, fluctuate widely. The ratio between exchangeable magnesium and calcium does not demonstrate the expected agreement with the salinity evolution of the Baltic. On the other hand, the ratios potassium/sodium, calcium/sodium, and magnesium/sodium in general show the expected evolution.

The Rödäng and Dynäs sites are similar as regards stratigraphy, colouring of the sediments, and chemical and technical properties. From north to south, through the three sites investigated the sediments become more fine-grained, their contents of organic matter lower and their colours lighter.

The shear-strength values from Dynäs are lower than those from Rödäng. Furthermore the distributions throughout the postglacial sections of the sequences are reversed. In the Rödäng core there is a slight increase downwards whereas in the Dynäs cores there is a decrease downwards. The sensitivity values determined in the Rödäng core chiefly represent a medium sensitive clay while the Dynäs core has values over 50, representing a quick clay throughout the sequence. The methods of determining the sensitivity do not always yield reliable results.

The exchangeable ions show a similar distribution within the Rödäng and Dynäs cores. However, the values are of different magnitude. The ground-water observations from Dynäs demonstrate fluctuations of 0.6 metres at most during a period of 90 days. These fluctuations may influence the pore pressure, especially in the confined aquifers which will perhaps in turn influence the behaviour of the ions in the interstitial water.

The results of this investigation indicate the unprecision of the methods for determination of consistency limits and sensitivity of this type of sediment. This is particularly true of the Dynäs sediments. Moreover, at Gammelgården the vertical fissuring prevented routine geotechnical tests.

In future the sulphide-bearing sediments should be investigated with special reference to the following problems:

the influence of the ground water and piezometric pressure changes on the technical and chemical properties of the sediments,

the lack of an adequate method of determining the consistency limits and the sensitivity,

the composition of the sulphide phases,

the mechanisms of water and ion binding in the sediments,

the composition of the interstitial water.

A report on comparisons of the fall-cone test, the field-vane test and the triaxial test on these types of sediments is in preparation.

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Symbols and designations used in text

γ	bulk density
w	water ratio
w_n	water content
w_L	liquid limit
w_p	plastic limit
I_p	plasticity index ($w_L - w_p$)
I_L	liquidity index ($w - w_p)/I_p$
τ_{fu}	undrained shear strength
τ_r	remoulded shear strength
S_t	sensitivity
σ'_{vo}	effective vertical *in situ* stress = consolidation pressure at triaxial test
A^o	in general the rational limit of *Alnus*, over one per cent *Alnus*
P^o	in general the rational limit of *Picea*, over one per cent *Picea*
B.P.	before present (1950)
r	correlation coefficient
s	significance
N	number of observation pairs
t	test quantity, student's t
RPD	redox-potential-discontinuity zone
Coarse clay	15–25 per cent clay } According to Glossary of Geology,
Medium clay	25–40 per cent clay } Swedish Centre of Technical Terminology,
Heavy clay	40–60 per cent clay } Publication in preparation.
Gyttja clay	Sedimentary soil, 2–6 weight per cent organic material content

Sampling

◎	Extraction of undisturbed samples, e.g. by means of piston sampler
St I	standard piston sampler
kv	piston sampler

Testing *in situ*

⌧	Determination of shear strength directly in the ground, e.g. by means of vane borer

Hydrological Determinations

♉	Ground-water table determination

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